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The sedimentology, palaeoecology and preservation of the Lower Carboniferous plant deposits at Pettycur, Fife, Scotland

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Abstract – The Lower Carboniferous (Asbian) sediments and volcanics of the Pettycur region in Fife, Scotland, yield several important anatomically preserved floras including that from the famous 'Pettycur Limestone'. The plant fossils are preserved as calcareous permineralizations and fusain within limestone blocks which occur at the base of basaltic lava flows or within pyroclastic sequences. The geology and sedimentology of these plant deposits have been investigated, and it is demonstrated that a number of plant-bearing facies can be recognized which reflect different modes of transport, deposition and fossilization. Of these facies the 'Pettycur Limestone' is the most well known. The lithology is composed of a distinct assemblage dominated by lycopods and the pteridosperm, *Heterangium*. Other assemblages include a limestone dominated by zygopterid ferns which are frequently fusainized and the Kingswood Limestone which contains a completely different flora to that at Pettycur, being dominated by pteridosperms, other gymnosperms and the lycopod *Oxroadia*. Each sediment type is characterized by a distinct mineralization history of the plants reflecting different sites of fossilization.

A hypothesis concerning the original ecology of the plant assemblages within the basaltic volcanic terrain is proposed. It is suggested that the Pettycur Limestone represents an established original peat within which the plants were permineralized. The zygopterid ferns occupied sites which were susceptible to wildfire and did not establish long-lived peat-forming communities. The Kingswood flora was established in a region where plants were prone to fire and then subsequently transported into an area of limestone deposition along with unburnt plant fragments. This flora was separated

1. Introduction

At Pettycur, East Fife, Scotland, plant fossils of Lower Carboniferous (Asbian) age occur as calcareous permineralizations closely associated with a series of basaltic lavas and intrusions. This flora represents one of the few examples of anatomically preserved plants of this age and has been known for over 100 years (Williamson, 1871 *et seq*); it includes some 20 type species and four genera types (Scott, Galtier & Clayton, 1984).

Permineralizations formed when the plant material was infiltrated with mineral matter at the cellular level giving rise to a fossil that is preserved in three-dimensions. Usually the organic matter of the cell walls is present in an altered state. Frequently this mineralization occurred early, before decay processes were advanced, as detailed anatomical information is often preserved (Schopf, 1975). This is in contrast to the preservation state known as petrification where during the mineralization a replacement of the cell walls occurred resulting in a fossil in which no organic material is preserved (Schopf, 1975). This is frequently the case in silicified wood (Scurfield, Sequit & Anderson, 1974). The most common permineralizing minerals are carbonate and silica but pyrites and limonite are known (Schopf, 1975).

Two other fossilization states of plant fossils are preserved at Pettycur. The most common of these are plant remains preserved as fusain or fossil charcoal (Scott & Collinson, 1978). The term is used here following the definition of Cope & Chaloner (1980) and Chaloner & Cope (1982) as a product of wildfire which resulted in the burning of the plant material. Less common at Pettycur are plants preserved as compressions where the plants have suffered compression and coalification resulting only in the external morphology of the plant being preserved (Schopf, 1975; Rex & Chaloner, 1983).

The object of the present work was to investigate in detail the plant deposits preserved as calcareous permineralizations within the Pettycur region. This has involved detailed studies of the geology and sedimentology of the area and analysis of the plant-bearing sediments. It is clear that there were some strong palaeoecological controls within the volcanic environment which the plants inhabited. The mineralogy and chemistry of the permineralizations was investigated in order to obtain a fuller understanding of this fossilization process in a volcanic terrain.

2. Historical background

The fossil flora of late Visean (Lower Carboniferous; Asbian) age from Pettycur was first discovered in the 1800s (reported by Gordon, 1909) in loose blocks of limestone within the beach deposits at Pettycur. Following this, specimens of the 'Pettycur Limestone' material were sent to Williamson who described several species (Williamson, 1872*a,b*, 1873, 1874, 1893, 1895). Subsequently other early workers included D. H. Scott (Williamson & Scott, 1895; Scott, 1898, 1900, 1901, 1920) and Kidston & Benson (Kidston, 1907, 1908; Benson, 1914).

The first concise account of the permineralized plant deposits at Pettycur was by Gordon (1909) who subsequently described several taxa (Gordon, 1909, 1910*a,b*, 1911*a,b*, 1912). In his first account of the geology of the Pettycur region, Gordon (1909) described not only the occurrence of the permineralized plants as eroded blocks on the beach but also *in situ* within the cliff section at Pettycur. He gave a brief account of the taxa preserved within the sediments and described the chemistry of the permineralizations demonstrating that there is a variation from calcium through to silica. At about this time Stopes & Watson (1908) published their classic paper on coal ball formation giving a chemical analysis of the components of the coal balls and postulated on the environment under which this type of permineralization may have occurred. Gordon (1909) offered a comparison with coal balls but concluded that the 'Pettycur Limestone' was not comparable with the coal-forming peat which is preserved in the coal balls. He proposed that the plants at Pettycur were washed into and permineralized within pools fed by mineral-rich thermal waters from the volcanic sources. He concluded that these deposits were periodically destroyed by volcanic eruptions and fragmented. Gordon (1914) subsequently reported that he had discovered impression fossils of plants within the ashes exposed at Pettycur but did not give any indication of the taxa present.

Many papers have subsequently described the flora at Pettycur and these have been summarized by Scott, Galtier & Clayton (1984). No attempt will be made here to review the flora or individual taxa.

The geology of the Burntisland–Pettycur region was first described in detail by Geikie (1900) who described the volcanic and sedimentary rocks from Burntisland–Kirkaldy. Along this section he noted that loose blocks of limestone-bearing permineralized plants occurred but did not encounter the limestone *in situ*. The igneous geology of the region was described later in more detail by Allan (1924) but he does not mention any plant fossils associated with the volcanic and intrusive rocks. Francis (1960) in his field guide of the region describes a plant-bearing limestone similar to the 'Pettycur plant bed' above Kingswood End. This may be the Kingswood Limestone described below. More recent investigations have shown the occurrence of *in situ* permineralized plants from localities at Pettycur and Kingswood (Scott, Galtier & Clayton, 1984; Scott *et al.* 1986; Scott & Rex, 1986).

3. Methods

The geology and sedimentology of the Pettycur region (Fig. 2a,b,) was investigated by mapping the area in detail and logging a number of key plant-bearing sections (Fig. 2c). Much new material was collected during the course of this work and this was slabbed and peeled using the techniques of Joy, Willis & Lacey (1956) and Stewart & Taylor (1965). The peels were initially used to identify the taxa present and to characterize the plant-bearing sediments. Normal and stained thin-sections (Alizarin-red and potassium ferrocyanide; using the techniques of Dickson, 1965) were used to identify the permineralizing minerals and the chemistry of the carbonates. More sophisticated chemical analyses were undertaken on polished thin-sections using a microprobe on a Jeol JSM-US SEM and some cement generations were identified using cathodoluminescence (Technosyn). The material used in this study is housed at Royal Holloway and Bedford New College. Selected specimens have been donated to the Royal Museum of Scotland.

4. Geology and stratigraphy

By the beginning of Carboniferous time Scotland had become part of the southern marginal shelf of the North American–North European craton (Francis,

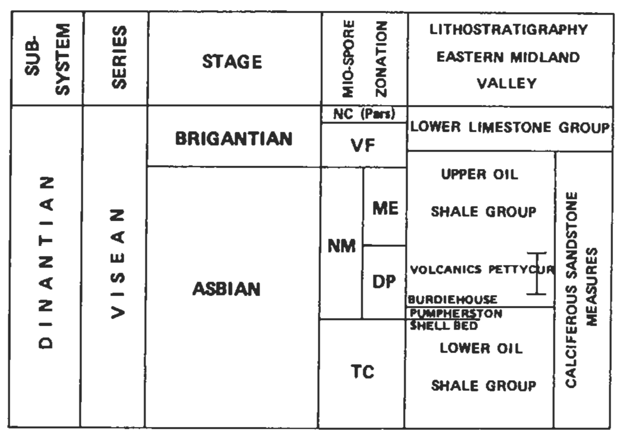

Figure 1. The stratigraphic position of Pettycur within the Dinantian (compiled from George *et al.* 1976; Clayton, 1986 and pers. comm.; Scott, Galtier & Clayton 1984; and Francis, 1983*a*).

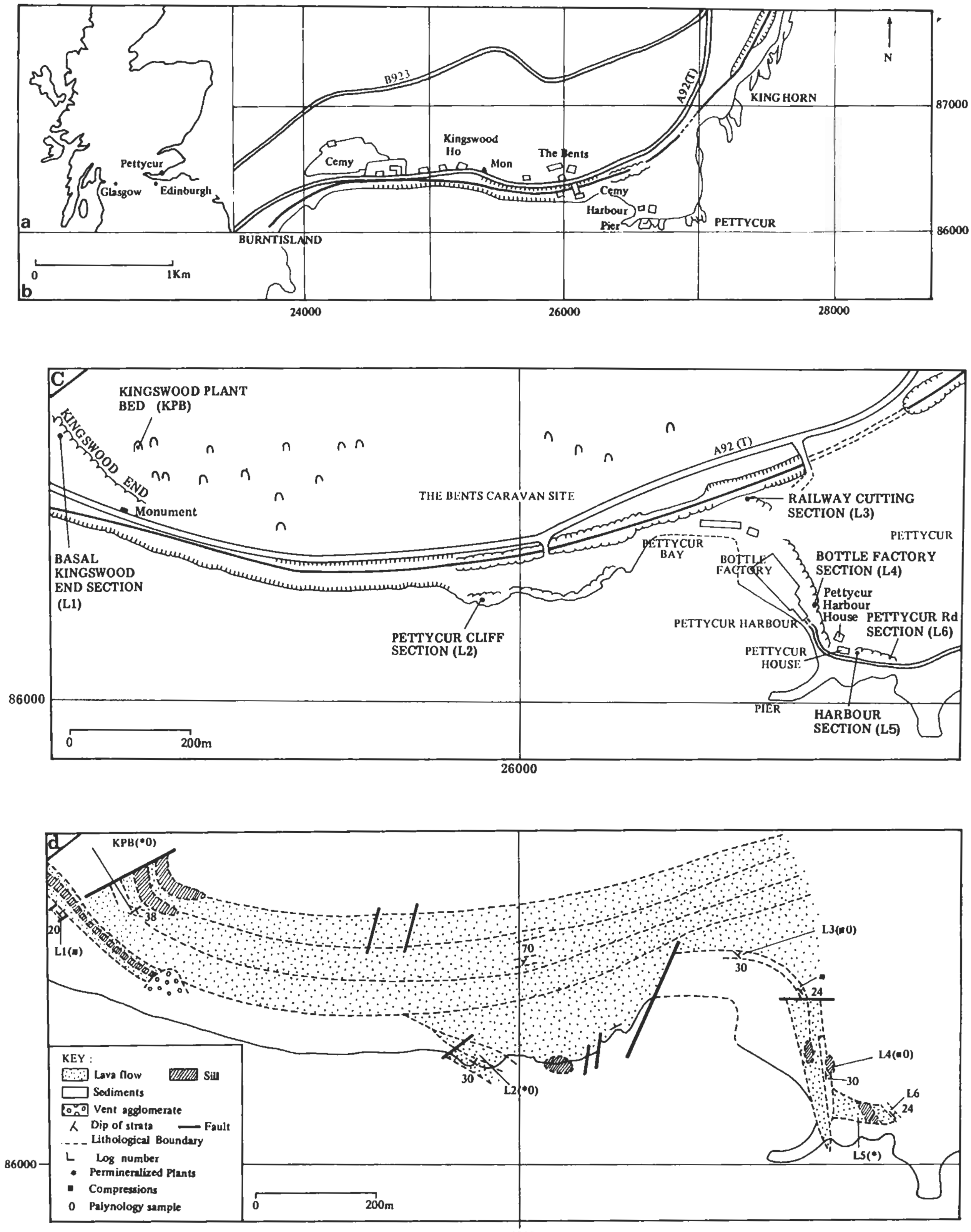

Figure 2. (a) Map of Scotland and northern England with the locality marked. (b) Sketch map of the area studied showing local landmarks. (c) Sketch map of the area studied showing the position of the lithological sections described in the text with accompanying log numbers. (d) Geological map of the area studied showing the positions of the lithological logs and the localities at which permineralized plants and plant compression fossils were found and palynology samples taken.

1983*a*) following the closure of Iapetus. Scotland at this time was bounded to the north by the Caledonian mountains, which supplied sediment into the Midland Valley, and south by the Rheic Ocean. Early Visean volcanism in the Midland Valley in the Clyde and Forth areas provided barriers to sedimentation resulting in the formation of a number of isolated basins, e.g. the Lothian oil shale basin (Francis, 1983*a*). This close inter-relationship of sedimentation and volcanism has been the subject of several papers (e.g. Francis, 1978, 1983*b*; Leeder, 1986). The volcanism has been considered to be the product of rift tectonics (Francis, 1978) perhaps related to the subduction of the Rheic Ocean to the south (Leeder, 1976, 1986) or else shear-zone faulting (Francis & Hopgood, 1970) or perhaps related to the opening of the North Atlantic (Hazeldine, 1984). By the late Visean the small basins of sedimentation in the Midland Valley were replaced by more widespread shallow seas in which shelf limestones fluctuated with deltaic sandstones and coals (Francis, 1983*a*). The stratigraphic position of the Pettycur locality with respect to the Midland Valley lithological divisions is shown in Figure 1.

4.a. Description of the sections

The area under discussion in this paper is on the east coast of Scotland on the Firth of Forth near the towns of Pettycur and Kinghorn (Fig. 2a,b). The section described has its most westerly boundary near the Kingswood Hotel (GR (grid reference): NS253865) and its easterly boundary near Pettycur House (NS267862) (Fig. 2c). It is predominantly a coastal section of approximately 2 km with some inland exposure. It is within this area that plants preserved as permineralizations and compressions occur closely associated with a series of basaltic lavas, dolerite sills, tuffs, agglomerates and sediments. The beds have a general easterly dip forming the eastern limb of the Pentland anticline. The general geology of the area as elucidated during the course of this work is shown in Figure 2d, and the relationship of the permineralized plant-bearing lithologies to the localities described is shown in Figure 3. In order to clarify the geology of this area under study it will be described in three sections: Kingswood End, Pettycur cliffs and Pettycur Harbour.

4.a.1. Kingswood End section (NS252865–260866)

This section begins at the base of the Kingswood End sequence of lavas and sills and extends across the large caravan site (The Bents) situated on the hills above Pettycur (Fig. 2c). A 10 m sedimentary section (Fig. 4a,b) occurs at the base of the thick sequence (approximately 100 m) of interbedded sills and lavas forming Kingswood End. The outcrop is only approximately 10–12 m wide and terminates sharply at its lateral margins. The section is composed of a series of massive yellow limestones which are often stromatolitic in the upper part interbedded with shales and graded ashes (Fig. 5c). Some of the shale layers contained plant compression fossils, some of which are well preserved. *Lepidostrobus* sp. (Fig. 13g) and *Lepidostrobophyllum* sp. were identified. The section was capped along the entire outcrop by the basal lava flow of Kingswood End.

LITHOLOGY	LOCALITY	SEDIMENT TYPE
Pettycur Limestone	Pettycur Beach	Mineralized Peat
Zygopterid Limestone	in situ Pettycur Cliff. Pettycur Beach	Micritic ashy Limestone
Ashy Limestone I	in situ Pettycur Cliff.	Micritic ashy Limestone
Ashy Limestone II	in situ Pettycur Cliff. Pettycur Beach	Micritic ashy Limestone
Ashy Limestone III	in situ Pettycur Cliff. Pettycur Beach	Micritic ashy Limestone
Harbour Peat	in situ Pettycur Harbour section	Mineralized peat
Kingswood Limestone	in situ Kingswood Plant Bed.	Brown Limestone

Figure 3. The relationship between the permineralized plant-bearing lithologies, localities and sediment types in the Pettycur region.

Kingswood End itself (Fig. 5a) is composed of a series of basaltic lavas and doleritic sills. Each individual lava flow is approximately 6–7 m thick whereas the sills are much thinner, reaching up to 3 m in thickness. Impersistent thin, yellow dolomitic mudstones outcrop between some of the lava flows and these contained some plant debris. The top of Kingswood End is capped by a highly weathered vesicular, amygdaloidal basaltic lava. The sequence of lavas and alternating sills continues through the hillside of the Pettycur caravan site and is folded into a shallow synclinal structure (Fig. 2d).

Within the shallow easterly dipping sills and lavas of these hills outcrop a series of interbedded agglomerates and tuffs. These are frequently laterally bounded by small steeply dipping faults. The most significant of these outcrops occurs not far from the top of Kingswood End and has been the subject of a previous paper (Scott *et al.* 1986). At this locality (NS255866) a series of agglomerates and tuffs outcrop dipping 38° SE. Within the agglomerates occur a number of large limestone blocks (Kingswood Limestone), which contain plants preserved as fusain and permineralizations. The entire sequence of lavas and sills forming the hillside dips and thins to the east. This rapid lateral thinning, which is characteristic of many of the lavas in the area, causes some problems in correlation. An agglomerate representing an ancient volcanic neck (Geikie, 1900; Allan, 1924) cuts the section at the southern end of Kingswood End above the King Alexander III monument (NS254865).

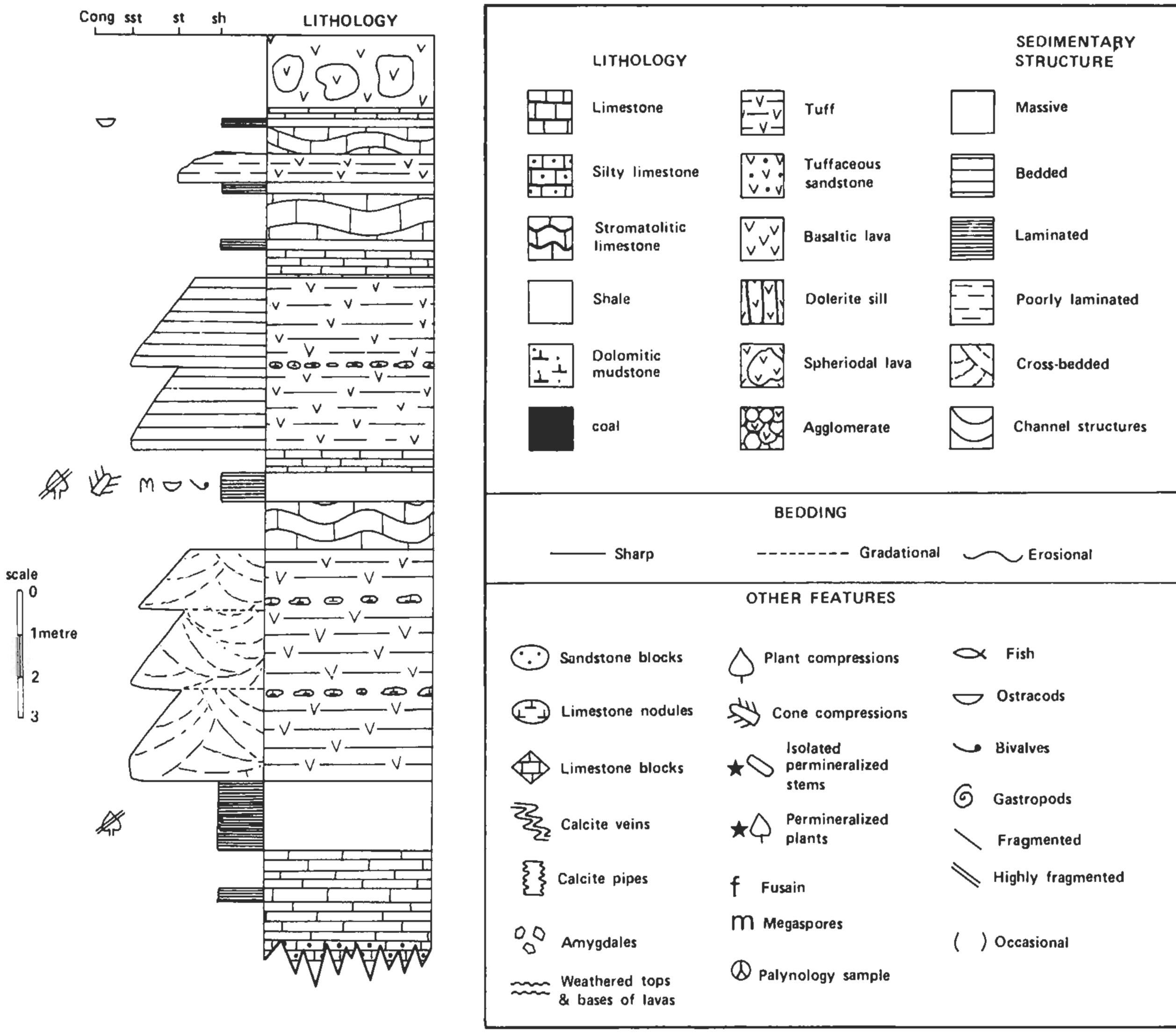

Figure 4. Lithological log (L1) of the basal Kingswood section, with legend to lithological logs for Figs. 4, 6–10.

4.a.2. Pettycur cliff section (NS260864–263865)

From the field relationships the series of lavas composing this section lies below the sill/lava complex of Kingswood End. The most important section within this area is that at Pettycur cliff (NS260863) (Fig. 2c, 5d). It is on the beach below this section that blocks of the Pettycur Limestone have been found over many years. More recently the plants have been found *in situ* (Scott, Galtier & Clayton, 1984; Scott & Rex, 1986) within Pettycur cliff but the Pettycur Limestone *sensu stricto* was never found *in situ*. The Pettycur cliff section (Fig. 6) is composed of three basaltic lava flows with a shale separating the lower two (Fig. 5g). It is at the base of the third basaltic lava that the plants occur within ashy limestone blocks up to 80 × 50 cm; these are usually sub-angular but the margins are often obscured by the lava matrix (Fig. 5e). Two different lithologies were recovered from the cliff: the zygopterid limestone and a series of ashy limestones all containing permineralized and fusainized plants. A series of carbonate vertical pipes (approximately 5 cm high and 1–2 cm in diameter) are locally developed above some of the sediment blocks at the base of the flow (Fig. 5e). The lavas of Pettycur cliff thicken towards the south east but are soon covered by the beach deposits of the foreshore. The remainder of the cliffs to the east of this locality are composed of a single large basalt flow which is periodically intruded by dolerite sills. The lava is cut out by a large NNE–SW fault running through the west side of Pettycur Bay (Fig. 2d).

4.a.3. Pettycur Harbour section (NS263865–267862)

This section extends from the eastern side of Pettycur Bay to just east of Pettycur House. The section begins against the main Pettycur Bay fault and it is difficult to ascertain the lateral and vertical relations of this section with the Pettycur cliff section. It is clear that

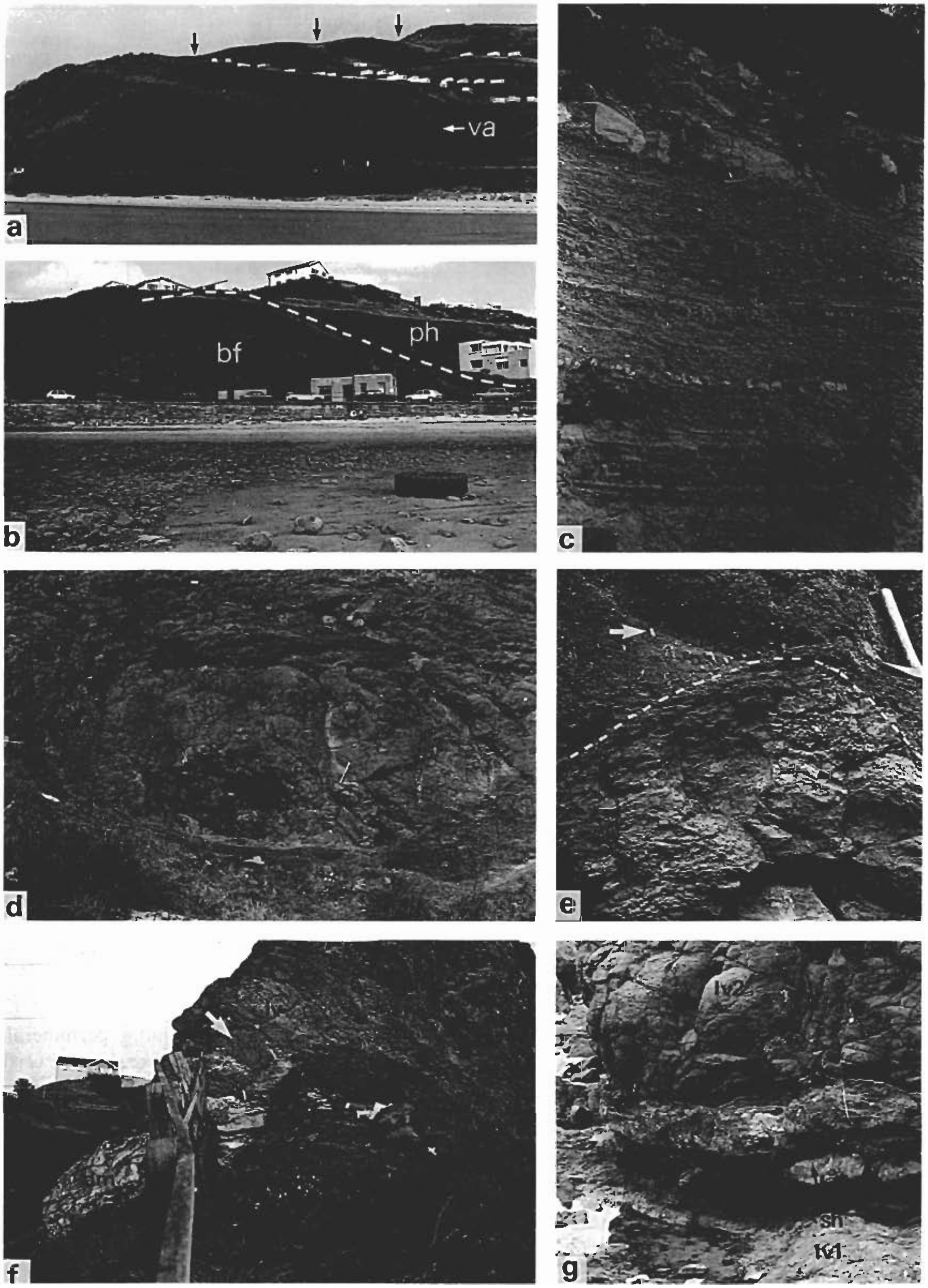

Figure 5. (a) The alternating sill and lava sequence of Kingswood End forming a series of ridges (arrows) through the hillside. These are cut by a vent agglomerate (va) at the eastern edge of the cliffs. (b) The Bottle Factory lava sequence (bf) thins southeast and is overlain by the Pettycur Harbour lava (ph). (c) The upper part of the basal Kingswood End section (L1), showing the sequence of limestones and interbedded ashes (geological hammer = 37 cm long). (d) The base of the third lava at Pettycur cliff section (L2). The hammer (arrow) is positioned just above a block of limestone containing permineralized plants. (e) The block of limestone shown in (d) within which a permineralized plant stem can be seen (black arrow). The dashed line represents the contact between the limestone and the lava. Vertical pipes of calcite occur in the lava above the block (white arrow). (f) The lower part of the railway cutting section (L5), showing the dolomitic mudstone (dm) underlying the basaltic lava flow (lv). A large block of the mudstone is incorporated within the base of the lava flow (arrow). (g) The base of the Pettycur cliff section (L2) showing the unit of shale (sh) (1 m thick) separating the first (lv1) and second (lv2) basalt lava flow.

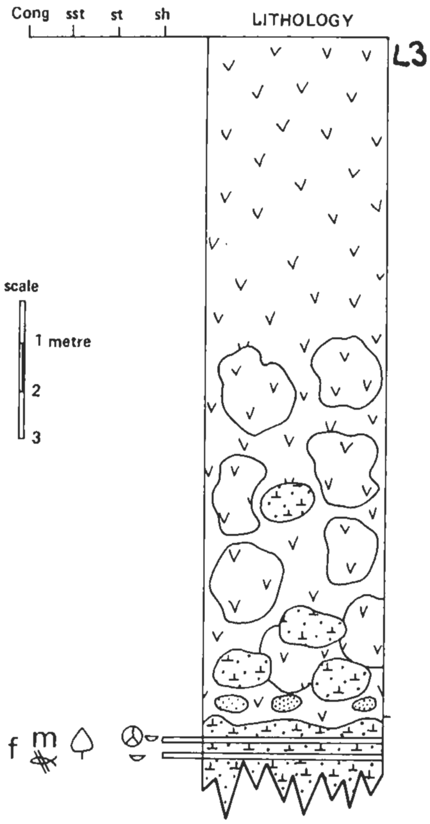

Figure 6. Lithological log (L2) of the Pettycur cliff section.

the section underlies the lava and sill sequence forming the hill side (The Bents) to the north but may well be the lateral equivalent of the Pettycur cliff section.

The lavas of the Harbour section are underlain by a thin sedimentary sequence which outcrops at the Railway Cutting section (Figs. 5f, 7). The mudstones within this sequence yielded some well preserved plant compressions, e.g. *Lepidodendron* sp. (Fig. 13j). These sediments are overlain by a thick lava flow (20 *m*) which is faulted out by an east–west trending fault. In the cliffs behind the former Bottle Factory a further series of lavas, sills and sediments outcrop. The Bottle Factory section (Fig. 8) is composed of two flows, the upper flow being columnar in part with the joints filled with tuff cemented in carbonate. The lavas are underlain and overlain by locally developed impersistent dolomitic mudstones. Of these, the mudstone above the second flow is the most persistent and appears to be developed within depressions in the old lava surface. In places this lithology yielded plant compression fossils, mainly of lycopods and pteridosperm leaves (Fig. 13f,e). Above this sequence a thick series of shales, silts and graded tuffs is exposed. This lava and interbedded sediment sequence thins southwards and disappears on the beach section at Pettycur Harbour.

A further major lava occurs above the Bottle Factory lavas. This lava is exposed behind Pettycur Harbour House and it thickens south eastwards. The base of the flow is well exposed and contains abundant

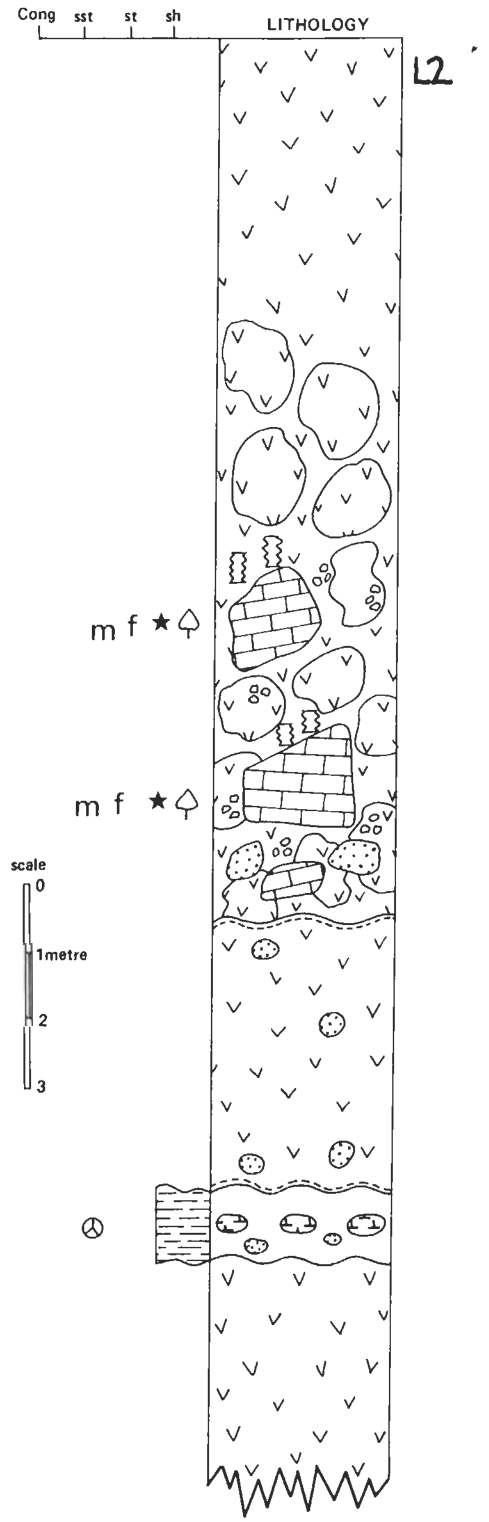

Figure 7. Lithological log (L3) of the railway-cutting section.

sediment fragments of barren limestones, baked shales and sandstones. Permineralized plant fossils were also found *in situ* at the base of this flow. The plants occurred not within subangular blocks as at Pettycur cliff but as strips of peat (Harbour Peat) wrapped around the spherical mounds of lava. In some cases the plant stems were directly incorporated into the

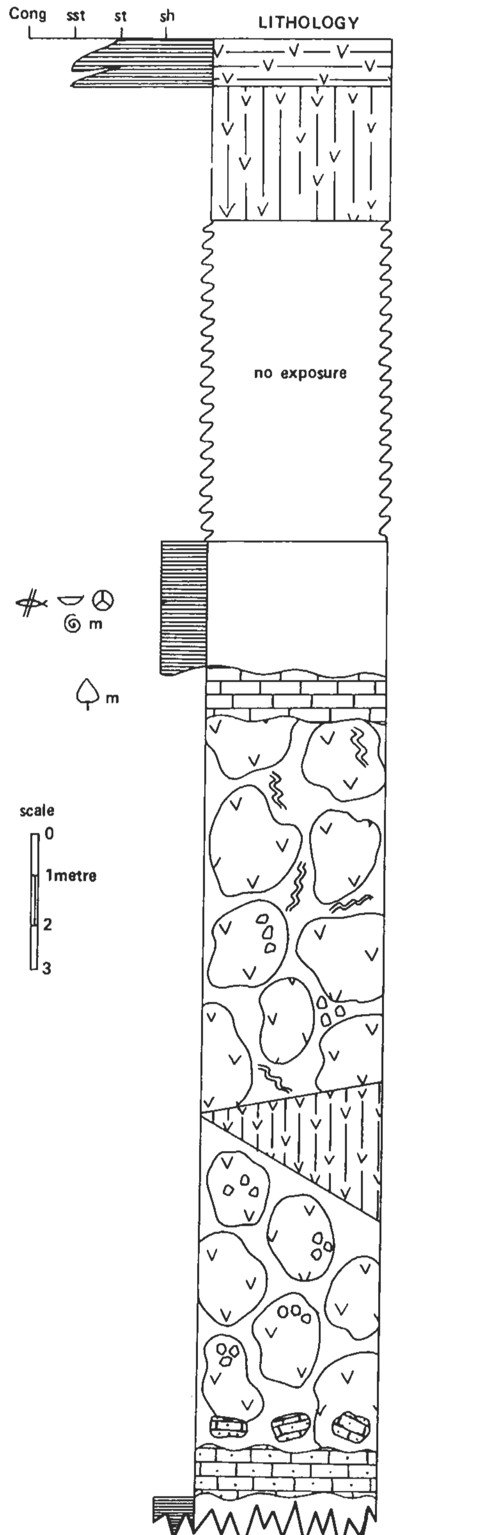

Figure 8. Lithological log (L4) of the Bottle Factory section.

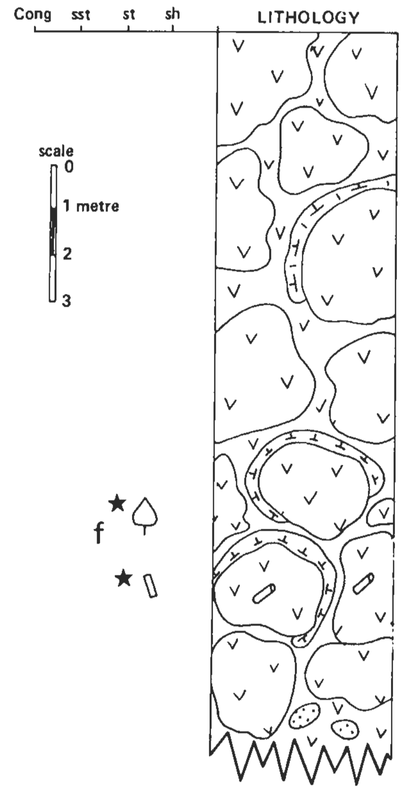

Figure 9. Lithological log (L5) of the Pettycur Harbour section.

lava. Plant material was only recovered at one section, the Harbour section (Fig. 9) just east of Pettycur House. The Harbour lava is intruded to the east by a large dolerite sill, above which outcrops a further flow which is overlain by a series of agglomerates, shales, a poor coal and graded tuffs, outcropping at the Pettycur Road section (Fig. 10).

5. The plant-bearing sediments

5.a. Anatomically preserved plants

The anatomically preserved plants in the Pettycur region occur within in a number of distinct lithologies which outcrop in specific localities (Fig. 3). These lithologies are dominated by certain taxa (Fig. 11) and are described below.

5.a.1. Facies 1a – Pettycur Limestone

This is the most famous of the plant-bearing lithologies at Pettycur and most closely resembles a coal ball peat (Scott & Rex, 1985). Generally within this lithology the plants are very well preserved, with the organic matter of the cell walls intact (Fig. 12a,b). The peat is characterized by a number of distinct taxa and by the absence of others. The most common peat-forming plant was the leafy lycopod *Paralycopodites brevifolius* (Will.) Dimich. which occurred with a number of bisporangiate cones, *Flemingites scottii* Jongs. (Brack-Hanes & Thomas, 1983). *Lepidocarpon wildianum* Scott was commonly associated with the lycopod stems and cones. The peat contained abundant rootlets of the lycopod rhizophore *Stigmaria ficoides* Sternb. The lycopod remains were generally concentrated into layers which were separated by layers of the only permineralized pteridosperm occurring at Pettycur, *Heterangium grievii* Will. (Fig. 12a). The sphenopsid *Archaeocalamites goep-*

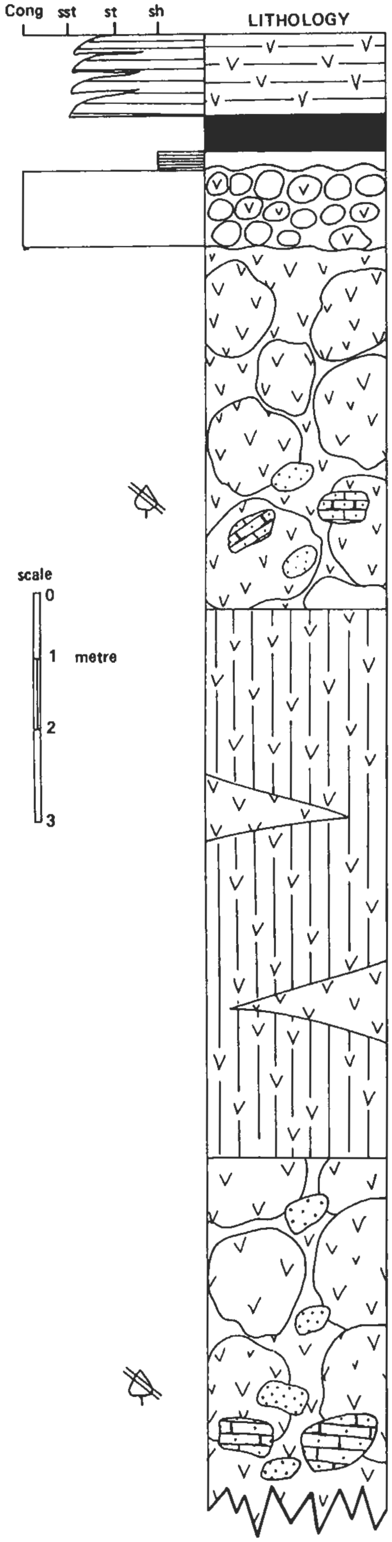

Figure 10. Lithological log (L6) of the Pettycur Road section.

pertii Solms was frequently preserved but often in the immature form. There are also two characteristic coenopterid ferns contributing to the peat, *Stauropteris burntislandica* Bert. (and its megasporangium *Bensonites fusiformis* Scott) and *Botryopteris antiqua* Kid. also with its abundant sporangia. These ferns were often concentrated in distinct monotypic layers (Fig. 12a). Rare examples of the sphenopsid *Sphenophyllum insigne* Will. and the lycopod *Lepidophloios scottii*. Jungs were observed.

The peat is devoid of clastic sediment and fragments of fusain were rare. Within many of the plant-bearing lithologies the zygopterid ferns were a dominant component of the flora but in this peat lithology they were noticeably absent.

5.a.2. Facies 1b – Zygopterid Limestone

In contrast to the lithology described above this sediment cannot be described as a peat, even though in part it has the aspect of a peat (Fig. 12c). This lithology has in the past been referred to as the Pettycur Limestone. The lithology is dominated by the two zygopterid ferns *Diplolabis roemerii* Solms and *Metaclepsydropsis duplex* Will. (Fig. 12c,d). These two ferns are preserved both as permineralizations and fusain, often concentrated into layers within the sediment (Fig. 12d). Frequently the ferns were preserved partially fusainized and permineralized. The zygopterid ferms are associated in the limestone with very large fragments of lycopod and poorly preserved *Heterangium grievii*. The plant material is frequently cemented and the plant organs filled with a yellow micrite which contains abundant clasts of fine-grained quartz. Frequently this lithology occurred as strips of peat wrapped around blocks of ash.

5.a.3. Facies 1c – Harbour 'Peat'

The Harbour 'Peat' was found as either narrow strips wrapped around the spherical mounds of lava, as peat fragments directly incorporated within the lava or as isolated stems. The quality of preservation of this 'peat' is not nearly as high as that of the other lithologies but components of the flora can be recognized. The most common plants are fusainized fragments of zygopterid fern cortex but some entire stems of *Diplolabis roemerii* (Fig. 12e) were preserved. These plants were incorporated in a matrix of organic debris within which examples of *Heterangium*, *Archaeocalamites* and *Paralycopodites* were occasionally recognizable. The peat contained abundant clastic fragments of lava, tuffs, amygdales and angular quartz grains.

5.a.4. Facies 1d – brecciated peats

These are composed of fragments of the Pettycur Limestone which have been recemented by silica or in some cases by a mélange of altered volcanic fragments (Fig. 12h). The characteristic peat flora *Heterangium–Paralycopodites–Botryopteris–Stauropteris–Archaeocalamites* was preserved.

SPECIES	LITHOLOGIES: PETTYCUR LST	ZYGOPTERID LST	ASHY LST I	ASHY LST II	HARBOUR PEAT	KINGSWOOD LST	BOTTLE FAC SEDS	BASAL KINGSWOOD SEDS
SPHENOPSIDS								
Archaeocalamites goeppertii	P		P		F	F		
Protocalamostachys pettycurensis	P							
Sphenophyllum insigne	P							
Cheirostrobus pettycurensis	P							
LYCOPODS								
Lepidodendron pettycurensis	P	F,P	F,P					
Paralycopodites brevifolium	P	F,P	F,P	F	F,P			
Lepidodendron sp.							C	
Lepidophlois scotii	P							
Flemingites scotii	P							
Lepidostrobus cylindricus	P							
Lepidostrobus sp.								C
Lepidostrobophyllum sp.								C
Mazocarpon pettycurensis	P							
Lepidocarpon sp.							C	
Stigmaria ficoides	P							
Oxroadia sp.						P		
Achlamydocarpon sp.						P		
FERNS								
Diplolabis roemeri		F,P	F		F,P			
Metaclepsydropsis duplex		F,P	F	F				
Musatea duplex		F,P	F	F				
Botryopteris antiqua	P		P					
Stauropteris burntislandica	P		P					
Bensonites fusiformis	P		P					
FERN-LIKE FOLIAGE								
Sphenopteris affinis							C	
Sphenopteris sp.							C	
Sphenopteridium sp.							C	
Adiantites machanekii							C	
Cardiopteridium sp.							C	
PTERIDOSPERMS								
Heterangium grevii	P	P	P		P			
Rheterangium arberi	P							
Sphaerostoma ovale	P							
Phytostoma sp.	P							
Lyginorachis sp.						F		
Kalymma sp.						F		
Phacelotheca pilosa						F,P		
Melissotheca longii						F,P		
GYMNOSPERMS *incerta sedis*								
Dadoxylon sp.						F,P		
Amyelon sp.						P		

Figure 11. The distribution of plant fossils within the Pettycur region. P = permineralizations, F = fusain, C = plant compressions.

Figure 12. The permineralized plant-bearing lithologies at Pettycur. (a) Pettycur Limestone lithology showing layering of the plant material. *Heterangium* (h), *Stauropteris* (s) and *Paralycopodites* (p), × 1.2. PEB15a. (b) The Pettycur Limestone showing the typical lycopod (p) and mass of stigmarian rootlets (sr), × 6. PEB15m. (c) The Zygopterid Limestone showing a peat aspect and containing many well-preserved *Diplolabis* (dp) petioles in a mass of organic debris, × 1.5. PEC16b. (d) The Zygopterid Limestone where the micrite matrix is extensively developed. The ferns occur as layers of fusain (fz) or as permineralizations (pz), × 0.7. PEB320c. (e) The Pettycur Harbour Peat. Highly fragmented lithology contains large fusainized *Diplolabis* (dp) petioles, × 1.2. PEH401a. (f) The Kingswood Limestone. The plants are either preserved as fusain (f) or permineralizations (p) in a micrite matrix, × 2.3. KIN245d. (g) Ashy limestone I composed of a mass of fusainized and permineralized fragments (arrows) in a micrite matrix, × 2. PEC320g. (h) Peat breccia composed of a large fragment of the true peat (arrow) cemented by silica and volcanic fragments, × 0.4. PEB408a. (i) Ashy limestone II composed entirely of fusainized (fz) zygopterid fern fragments cemented by micrite, × 1.8. PEB242f. (j) Ashy limestone III composed of fragmentary plant material; here a large fusainized lycopod stem is incorporated in the micrite, × 1.5. PEB2a.

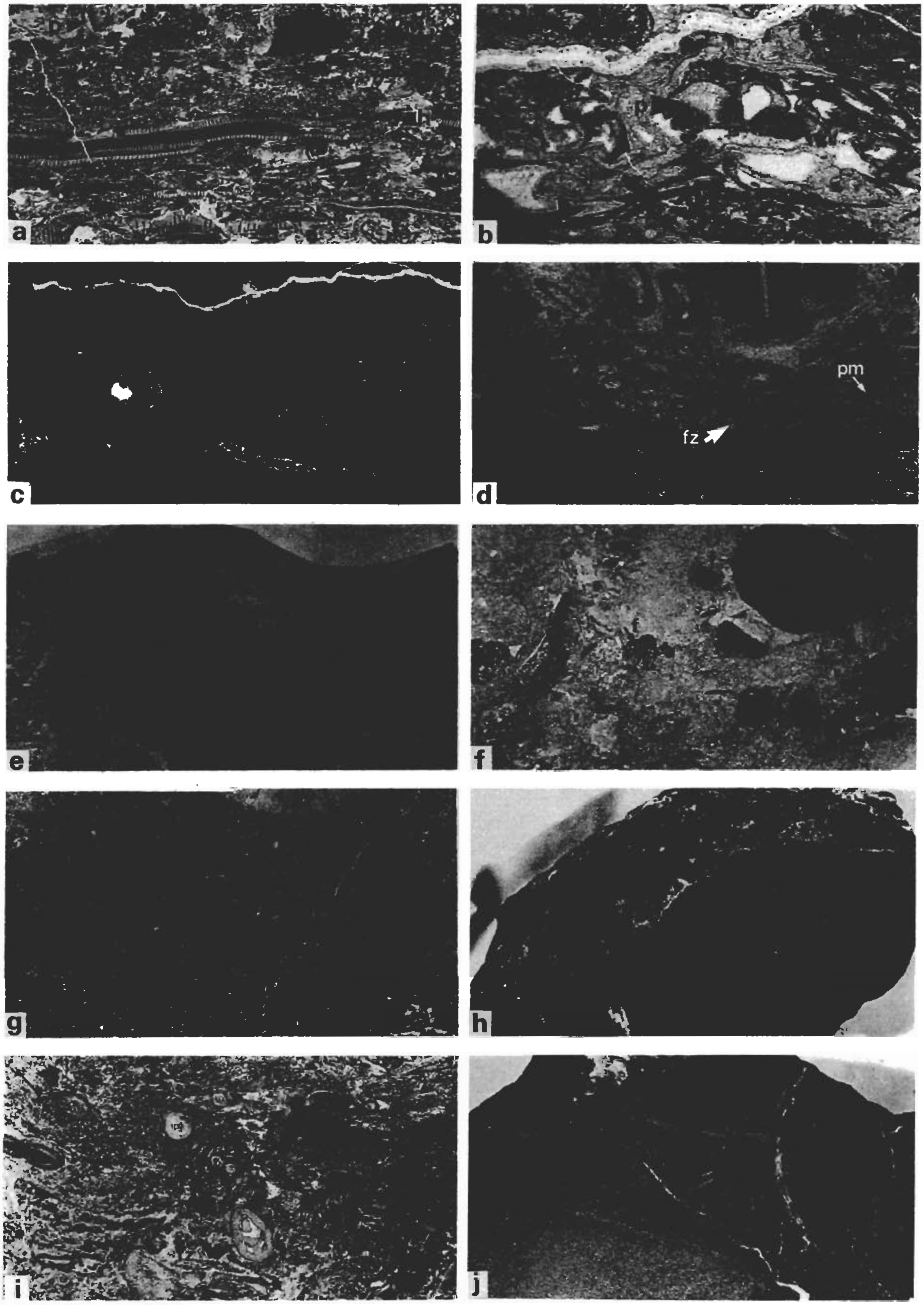
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Figure 13. The plant compression fossils found in the Pettycur region. (a) *Sphenopteris affinis* L & H, × 3. RSM 1985. (b) *Cardiopteridium* sp. and *Sphenopteridium* sp., × 3. RSM 1985. (c) *Sphenopteris affinis* L & H, × 3. RSM 1985. (d) *Adiantites machanekii* Stur., × 3. RSM 1985. (e) *Sphenopteridium* sp., × 8. RSM 1985. (f) *Lepidodendron* sp. Poorly preserved compression, × 1. RSM 1985. (g) *Lepidostrobus* sp., × 1. RSM 1985. (h) Lycopod cone scale, × 3. (i) *Lepidocarpon* cf. *waltoni* Chal., × 3. RSM 1985. (j) *Lepidodendron* sp. Compression of branch showing attached leaves, × 1. RSM 1985.

5.a.5. Facies 2 – Kingswood Limestone

This is a brown, fine-grained limestone which is frequently laminated and contains abundant fragments of plant preserved as fusain and permineralizations (Fig. 12h). The interest of this plant bed is twofold; firstly it is the only example of this type of lithology in the area under discussion and, secondly, it contains a very different flora from that preserved less than a kilometre away at Pettycur cliff. The flora at Kingswood is dominated by a number of pteridosperms and gymnosperms preserved as fusain. This is in contrast to the flora at Pettycur where these are very rare. The only lycopod present in the limestone is *Oxroadia*, preserved as a permineralization; this was never encountered at Pettycur. The common lycopod genus *Paralycopodites*, abundant at Pettycur, was never encountered in the Kingswood Limestone. The ferns and sphenopsids that are also abundant at Pettycur were rarely recorded at Kingswood. Details of the flora are given in Scott *et al.* (1986) and detailed studies of the pteridosperm pollem organs have been made by Meyer-Berthaud & Galtier (1986) and Meyer-Berthaud (1986).

5.b. Anatomically preserved plants within ashy limestones

5.b.1. Facies 3a – Ashy Limestone I

This is the most common type of ashy limestone at Pettycur. It is distinctly green in hand specimen and is often laminated. The limestone is composed of fine angular detrital quartz, silt fragments, pre-existing volcanic clasts and contains abundant highly fragmented permineralized (Pettycur Limestone flora) and fusainized (zygopterid flora) plant material (Fig. 12g). These fragments are cemented by a green micrite.

5.b.2. Facies 3b – Ashy Limestone II

This is a very distinctive lithology since the plant material within the limestone is completely fusainized. The fusain fragments are cemented in a fine yellow micrite which contains few clastics compared with the main ashy limestone. Many of the blocks are monotypic in fossil content containing only fusainized zygopterid ferns (Fig. 12i). Very rarely fragments of *Botryopteris* and *Archaeocalamites* were recognized.

5.b.3. Facies 3c – Ashy limestone III

Along with the major plant-bearing sediments described above were a number of fine-grained ashy limestones containing fragments of permineralized and fusainized plants (Fig. 12j). The degree of preservation was poor and again the clastics and plants were cemented by a green micrite containing detrital quartz and organic fragments.

5.c. Plants preserved as compressions

Plant compressions occur at several levels in the area (Fig. 11) and generally occur within dolomitic mudstones which occur as small impersistent beds on the top of basaltic lava flows. At Kingswood End poorly preserved lycopod axes and cones were found in a mudstone near the top of the sill/lava sequence. Several cones of *Lepidostrobus* sp. were recovered from shales at the base of the sequence (Fig. 13g).

Plant compressions were also collected from the dolomitic mudstone outcropping near the Bottle Factory and included *Lepidodendron* sp. (Fig. 13j), *Sphenopteris affinis* Lind. & Hutt. (Fig. 13a) and *Sphenopteridium* sp. (Fig. 13e). The most abundant compression flora was recovered from the dolomitic mudstones at Pettycur Harbour and the taxa included *Cardiopteridium* sp. (Fig. 13b), *Sphenopteridium* sp. (Fig. 13b), *Sphenopteris affinis* (Fig. 13c), *Adiantites machanekii* Stur. (Fig. 13d), *Lepidocarpon* cf. *waltonii* Chal. (Fig. 13i) and a lycopod cone scale (Fig. 13h). The most significant feature of this compression flora at Pettycur is the abundance of presumed pteridosperm foliage. This contrasts with the permineralized floras where pteridosperms are only represented by one taxon *Heterangium grievii*. Lycopods in comparison are dominant throughout the sequences.

6. Mineralogy and chemistry

6.a. The mineralogy and chemistry of the permineralized plants

6.a.1. Pettycur Limestone

This lithology has a very distinctive mineralogy and chemistry. The carbonate has always crystallized in the form of small dog-tooth crystals which are especially well developed in void fills (Fig. 14a). The permineralization, from the study of void fills within the peat, occurred in four distinct episodes:

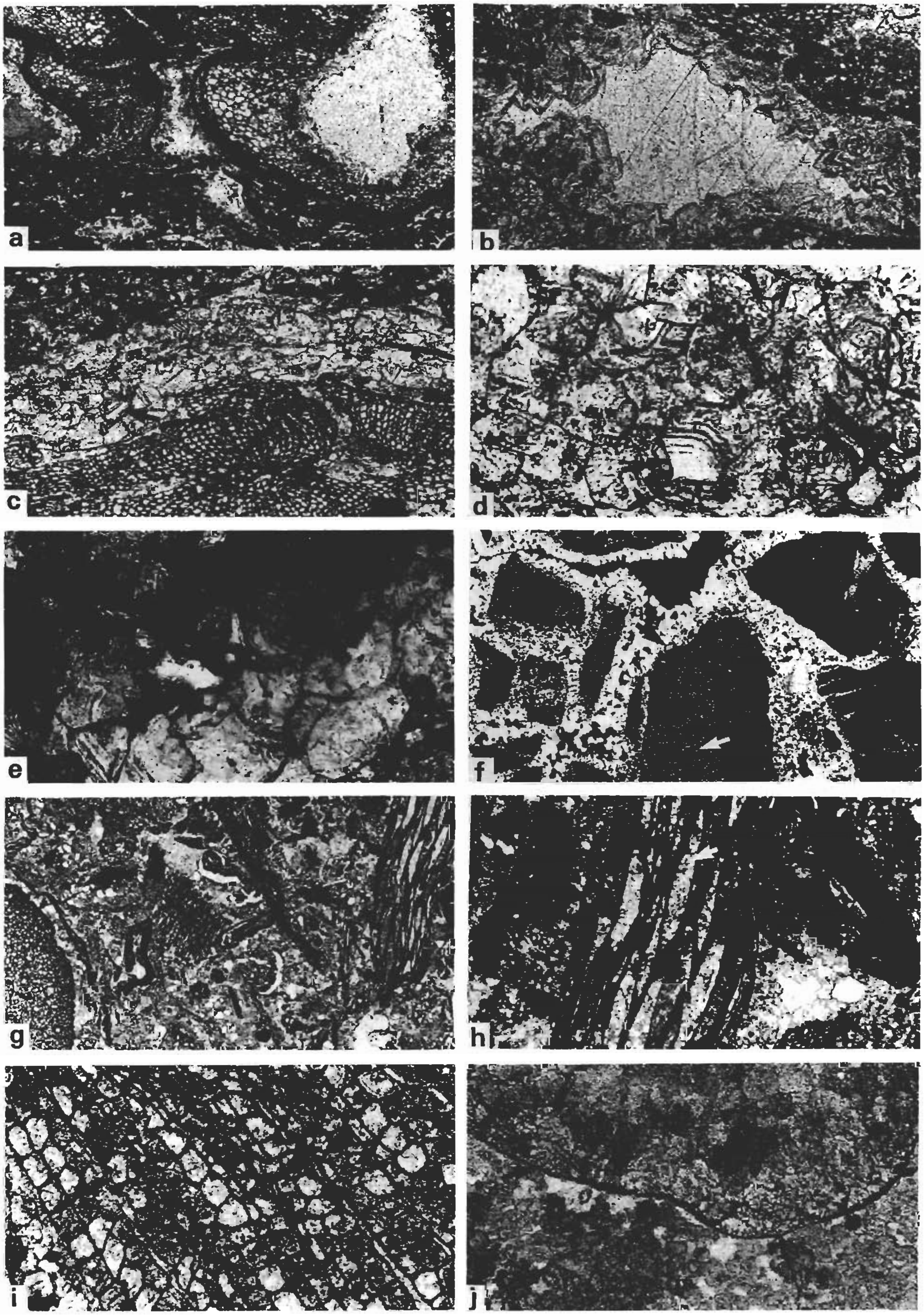
(1) The earliest formed carbonate was ferroan calcite forming small zoned dog-tooth crystals lining the void fills.

(2) A more persistent phase of Mg-rich calcite crystallization resulting in larger dog-tooth crystals.

(3) A phase of small zoned dog-tooth calcite crystals.

(4) The final phase of carbonate mineralization is represented by coarse-grained anhedral sparite crystals composed of ferroan calcite which fill the centre of the voids.

At the cellular level the cells are filled with zoned dog-tooth crystals which have nucleated on the cell walls (Fig. 14c) and grown out into the intracellular space. These crystals are most well developed in the larger cells where crystal formation was less confined, and these show distinct zoning (Fig. 14d). The stained sections indicate that the chemistry of the carbonate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within the cells fluctuates from calcite to ferroan calcite as indicated by the stripping of the stain in the cell fills. It was not easy though to recognize precise changes in the chemistry of the cell fills and a microprobe was subsequently used. The results of this demonstrated that the earliest formed calcite in the cell was Mg-rich but the Mg content decreased towards the cell centre. The analyses also showed that there was substantial silica, as quartz, within the cell fills. This occurred either as late stage filling around the dog-tooth crystal in the intracellular cavity or in some cases entire cells were filled with quartz. Silica had frequently replaced the calcite during diagenesis as relic zones of calcite could be seen included within the quartz crystals of cell fills (Fig. 14e). In some of the more siliceous peats this replacement is considerable and is accompanied by quartz at the centre of void fills (Fig. 14b). The evidence indicates that silica entered the system as a permineralizing mineral after all carbonate mineralization had terminated. Recrystallization of the calcite within the peats was never observed.

The peat breccias composed of previously mineralized peat which had suffered brecciation contained abundant silica. The peats were originally permineralized in carbonate but often within the cell fills the calcite has been replaced by silica (Fig. 14f). The recementation of the breccia began as fine fibrous quartz nucleated on the peat fragments (Fig. 14f). This was followed by the formation of coarse-grained euhedral quartz which filled the fractures between the peat fragments (Fig. 14f). Here again therefore there is evidence of substantial late silica percolating through the system.

6.a.2. *Zygopterid Limestone*

The mineralization of this limestone is in complete contrast to the Petttycur Limestone. The plant organs are filled and supported by a calcite micrite (Fig. 15a,c). The micrite matrix frequently contains abundant angular quartz grains around which calcite has frequently recrystallized. This has resulted in a concentric zoning of calcite around the clasts. This feature is most clearly seen in cathodoluminescence (Fig. 15b). At the cellular level the cells are filled with the same micrite as forms the matrix. The micrite within the cells fluctuates between calcite and ferroan calcite in composition and in the larger cells of the steles of the zygopterid ferns is zoned with an early generation of calcite and a later generation of ferroan calcite filling the centre of the cell. Again this zoning of the cell fills was only evident under cathodoluminescence (Fig. 15d). The chemistry of the cell fills does fluctuate considerably. Figure 16 shows a plot of the chemistry of the micrite within three adjacent cells in the cortex of a *Metaclepsydropsis*. One cell fill is dominantly calcium carbonate, the second shows high silica, iron and magnesium peaks and these substantially increase in the third.

6.a.3. *Harbour 'Peat'*

This again shows several different features to the lithologies described above. In contrast to those described above this peat contains abundant clastic components composed of volcanics, tuffs, and silts. Distributed throughout the peat are abundant detrital quartz grains. The peat is cemented by fine-grained calcite and ferroan calcite was rare. One of the most distinctive features within the peat is the presence of large, anhedral calcite crystals overgrowing the plant material (Fig. 17c). These crystals are usually developed within plant material adjacent to volcanic fragments. At the cellular level the cells are filled with a fine mosaic of calcite crystals.

6.a.4. *Ashy limestones*

Within all the ashy limestones the mineralogy and chemistry were constant. The limestones are essentially calcite micrites which support numerous detrital fragments (Fig. 14g). Recrystallization of these micrites is extremely rare. Silica was not present as a permineralizing mineral, only in the form of detrital quartz grains. The cells were all filled with the calcite micrite (Fig. 14h,i). There was little development of ferroan calcite; it only occurred within late fractures

Figure 14. Details of the plant permineralizations (all photographs from thin-sections). (a) Pettycur Limestone showing void fill within a lycopod leaf cushion. The void is lined in dog-tooth calcite and filled at the centre with a large sparite crystal, × 13. PEB15m. (b) Pettycur Limestone showing a void fill lined in dog-tooth calcite; the centre here though is filled with a quartz crystal, × 26. PEB425a. (c) Pettycur Limestone showing the development of dog-tooth zoned calcite crystals infilling cells (arrows), × 26. PEB15m. (d) Zoned cell fills of dog-tooth calcite in the Pettycur Limestone, × 60. PEB15m. (e) Replacement of calcite by quartz in the cell fills in the Pettycur Limestone. Relic zones of calcite can be seen preserved within the quartz crystal now filling the cell, × 115. PEB425a. (f) Peat breccia where in a number of the fragments of peat the carbonate filling the cells has been replaced by silica (gf). The breccia has been recemented by silica which has nucleated on the peat fragments (q), × 36. PEB408d. (g) Ashy limestone I showing a mass of plant fragments and angular quartz grains cemented by micrite, × 12. PEC440. (h) Plant fragments in ashy limestone I in oblique longitudinal section showing the fine micrite filling the cells, × 20. PEC440. (i) Plant fragment in ashy limestone I in transverse section showing the micrite filling the cells, × 26. PEC440. (j) Kingswood Limestone showing a transverse section of an *Oxroadia* stem (ps) in which the cell fills have recrystallized forming a mosaic structure of anhedral calcite. The cell walls are poorly defined as a result of this process. The actual matrix (m) is a calcite microspar, × 26. KIN247c.

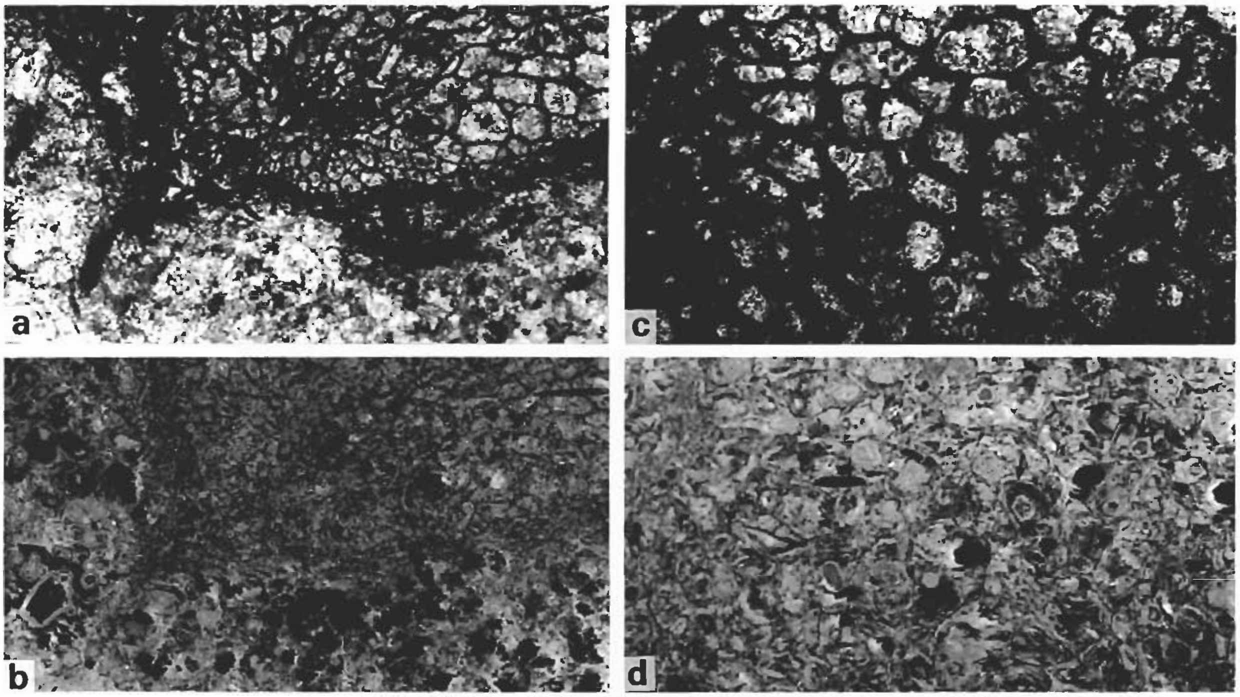


Figure 15. The structure of the micrite in the Zygopterid Limestone using cathodoluminescence. (a) Transverse section of a *Metaclepsydropsis duplex* showing part of the stele and the micrite fill of the pith cavity, × 100. PEC1. (b) In cathodoluminescence the quartz grains in the fill of the pith cavity (arrows) are clearly defined and show successive coatings of calcite, × 100. PEC1. (c) Detail of the cells in the stele of the *Metaclepsydropsis* stem, × 400. PEC1. (d) The same cells in cathodoluminescence showing the zoning of the micrite (arrows) within the cell fills, × 400. PEC1.

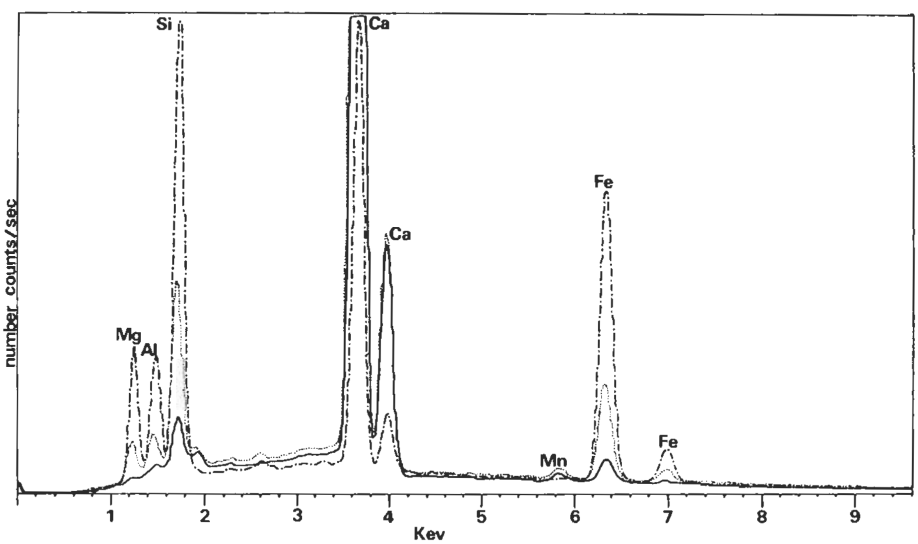


Figure 16. Graph showing the result of microprobe analyses of three adjacent cells in the cortex of zygopterid fern *Metaclepsydropsis duplex*. One of the cells (solid line) is composed almost entirely of calcium carbonate. In the second cell (shown by dots) calcium carbonate is still abundant but silica, aluminium, magnesium and iron appear. In the third cell (dots and dashes) the silica, magnesium, aluminium and iron levels have increased substantially. The horizontal axis is a function of the atomic energy of the elements and the vertical axis is the number of counts made each second for each element.

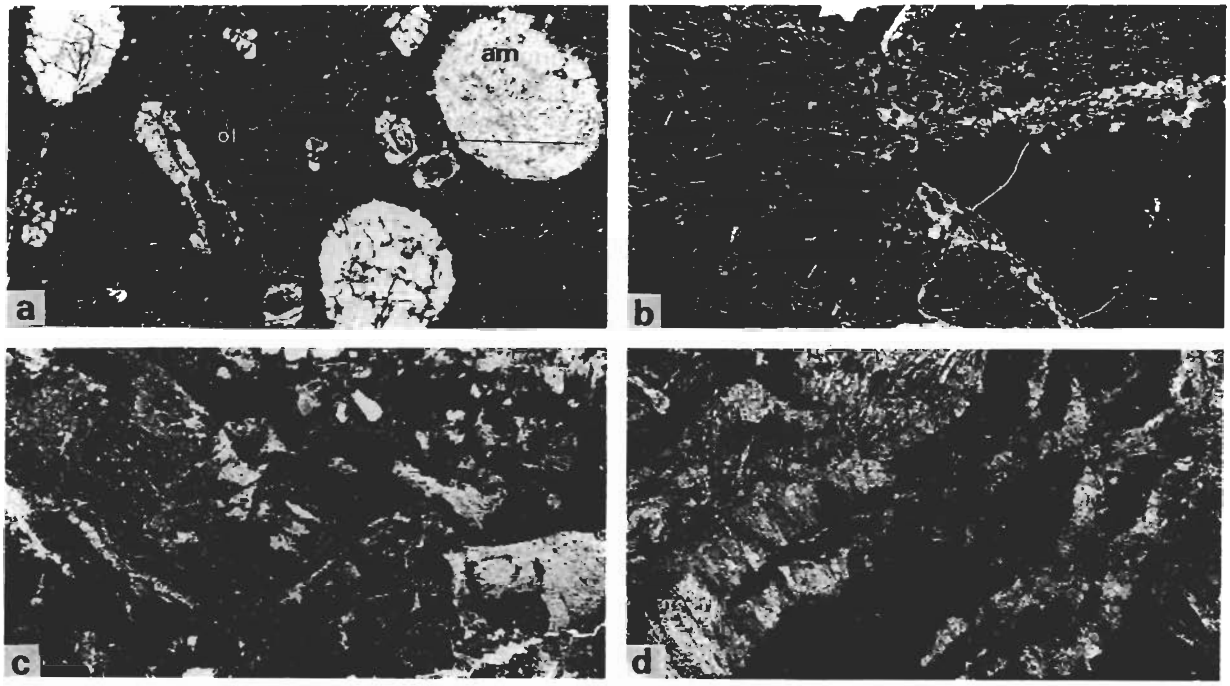


Figure 17. The lavas at Pettycur. (a) Typical olivine basalt showing a large calcite-filled amygdale (am) and pseudomorphed olivine (ol) phenocrysts in a fine-grained groundmass. Specimen from Pettycur cliff, × 14.5. (b) The Pettycur Harbour lava composed of a mélange of tuff fragments and amygdales in a basaltic groundmass, × 14. (c) Pettycur Harbour Peat showing a fragment of permineralized plant which has been overprinted by large euhedral calcite crystals (arrows), × 26. (d) Pettycur Harbour lava showing a network of fine fibrous calcite veins which occur abundantly through the lava, × 32.

cross-cutting the limestones. In some of the fine ashy limestones the plant debris has been overprinted by coarse euhedral crystals of calcite which had destroyed cellular detail.

6.a.5. Kingswood Limestone

This is the only plant-bearing limestone (except for the Pettycur Limestone) containing little fine-grained detrital material and to have been completely recrystallized to a calcite microspar (Fig. 14j). Within this microspar are patches of neomorphic spar of ferroan calcite. The pith cavities of plant organs such as *Oxroadia* show several episodes of mineralization. There is an early phase of calcite crystallization and this is followed by coarse ferroan calcite, as sparite, filling most of the cavity. Also present, though, within these void fills and within the matrix are distinct zones of quartz, which may be a late stage feature or a replacement. There is clearly also an earlier stage of silica generation as many cells are filled with quartz crystals. The permineralized plant fragments were originally filled with the early micrite but this has also undergone recrystallization and large anhedral calcite crystals, optically continuous between several cells, have formed (Fig. 14j). This has resulted in poor cellular preservation. The fusainized plant fragments, which are abundant in the limestone, are filled with fine-grained calcite.

6.b. The mineralogy and chemistry of the lavas

The lavas throughout the region under study were generally uniform. They are highly weathered, spheroidal in appearance (similar to pillow structures), prophyritic and amygdaloidal with extensive carbonate veining throughout. The lavas were mainly olivine basalts but some were locally doleritic. Olivine was the most abundant phenocryst but was always pseudomorphed and altered to calcite and quartz (Fig. 17a). The pyroxene, augite, formed smaller subhedral phenocrysts. The groundmass was composed of highly calcic plagioclase laths, anhedral titano-magnetite and was locally glassy. The amygdales reached up to about 1–2 cm in diameter and were either filled with fine, spherulitic calcite, a mosaic of anhedral calcite (Fig. 17a) or showed an early iron layer with silica developed at the centre.

The lavas at Pettycur Harbour differed in that they were not simply lavas but a mélange of plant debris, tuffs, quartz grains and lava fragments all incorporated in a highly amygdaloidal basalt lava (Fig. 17b). The lava was characterized by large quantities of calcite overgrowing the groundmass and a complex network of fine calcite-filled veins (Fig. 17d). Here again, the olivines had been pseudomorphed by calcite and the amygdales filled by carbonate.

6.c. Interpretations of fossilization

The mineralogy of the lithologies containing the anatomically preserved plants is not constant and each sediment-type exhibits a distinct mineralization. The outcrop, sedimentology, mineralogy and chemistry of the plant deposits provides some evidence to the fossilization processes that led to the formation of this type of plant fossil. Several distinct forms of permineralization have been recognized.

The Pettycur Limestone most closely resembles coal ball mineralization even though the fossils do not occur within rounded concentrations or within coal seams (Scott & Rex, 1985). The structure of the carbonate in the Pettycur Limestone is substantially different from the characteristic fibrous mineralization within coal balls (Scott & Rex, 1985). The carbonate within the Pettycur peat is distinctive and developed as dog-tooth crystals on cell walls and on the margins of void fills. The chemistry of the carbonate varies from calcite through to ferroan calcite but there is frequently a late silica generation. It seems evident from the abundance of lycopod rootlets within the limestone that this lithology represents an original *in situ* peat which was established within the region. Mineralization occurred within this peat while it was still in place and before compaction and decay processes were advanced, as is demonstrated by the high quality of preservation. Carbonate-rich solutions, which permeated the peat-swamp from time to time, fluctuated in chemical composition eventually becoming siliceous at a late stage. This change from carbonate to silica indicates a drastic alteration in the source of the fluids. Following this siliceous phase of mineralization, during which carbonate was replaced, the peat did not undergo any further recrystallization or replacement.

Two phases of reworking of this peat can be recognized. Firstly, an early phase of brecciation, after the lithification of the peat, probably as a result of a nearby eruption, ended by a phase of late silicification which replaced some calcite and cemented the breccia. Secondly, the peat deposit was ripped up, following lithification, and blocks of the limestone were transported in the base of a lava flow which swept over the area. The Pettycur limestone occurs as large angular blocks and it seems that peat formation and permineralization had halted some considerable time before final incorporation into the lava. There is no evidence that this lithology was still forming and transported wet or semi-permineralized within the basalt.

Gordon (1909) considered the fossilization history of the plants at Pettycur. He concluded that the plants were permineralized by hot springs into which plant debris floated. It seems clear, from the nature of the deposit, that the Pettycur Limestone represents the mineralization of a small peat swamp established within the volcanic environment and was not permineralized after transport into an area of fossilization. Gordon (1909) also reported on the occurrence of silica as a permineralizing mineral but considered that it was all original and not replacing carbonate. Examination of the mineralogy shows that this is not always the case and often silica has replaced calcite. He also suggested that some of the plants were permineralized by a tufa-type source. Modern tufas deposit calcite as a series of fine layers of carbonates on plants growing close to the spring waters (Pettijohn, 1957). No such development of carbonate was observed in the plant fossils at Pettycur and it seems that this type of process was not involved in the permineralization.

The Zygopterid Limestone was clearly not permineralized in the same manner as the Pettycur Limestone and this seems to reflect the original ecology of the plants. These ferns appear to have been growing on a site that was frequently exposed to burning as they are often fusainized. The lithology is often quite 'peaty' in that it contains permineralized and fusainized plants in a debris of poorly preserved compacted plant matter. The plants, though, are filled and cemented by micrite. It seems that these plants did not live in a peat habitat similar to that which gave rise to the Pettycur limestone. The ferns may have established small-scale peaty areas which were frequently burnt and this implies a growth site near a volcanic centre. The fragmentary nature of the Zygopterid Limestone suggests that the plants were transported either as individual organs or as small peat masses into a small lake or pool, in which micrite was being precipitated and detrital material washed in. The lithified Zygopterid Limestone was ripped up after formation and blocks incroporated into the base of a lava flow.

The Harbour Peats seemed to have been fossilized by a different process. This lithology seems to represent a type of poorly preserved zygopterid peat which seems to have not been permineralized before transport in the base of a flow. The peat outcrops as long strips wrapped around lava spheres and not as angular blocks. Therefore, it appears that the peat was caught up by the lava flow while still 'wet' and incorporated within it. The lava at the harbour section shows extremely extensive secondary calcite overgrowing the groundmass and it seems likely that there was sufficient carbonate permeating through the lava to have permineralized the plants. The general poor level of preservation except in the fusainized fragments seems to support a late fossilization within the lava.

Many of the ashy limestones containing permineralized plants show a mixing of the two Pettycur floras, the Pettycur Limestone flora and the Zygopterid Limestone flora. The highly fragmentary nature of the plants indicates the plants were transported some distance and the frequent layering of the ash seems to indicate they were deposited into a lake or pool along with a mass of debris from the volcanic activity. The plants were subsequently permineralized in this environment by calcite in the form of micrite. One type of ashy limestone contains only fusainized remains of zygopterid ferns and represents transport only from the zygopterid fern growth site with no intermixing with the Pettycur Limestone flora.

The Kingswood Limestone represents another environment of permineralization. The laminated nature of the sediment seems to indicate that this limestone is lacustrine in origin. This lake could not have had a peat type flora established on it or along its margins as the highly fragmentary nature of the plants implies thay have been transported before fossilization. This is the only plant-bearning sediment that has recrystallized and is texturally completely different from the other plant-bearing sediments. Following lithification this limestone was destroyed by an eruption and now only occurs as large blocks in an agglomerate. The angular nature of the blocks and the agglomeratic matrix indicates that the blocks were probably not transported as far from the site of fossilization as those blocks in the base of flows at Pettycur.

Small pools formed on the lava surface in which calcareous mudstones were deposited; these have subsequently recrystallized to dolomitic mudstones. Interestingly, within these pools only compression fossils are found even though some carbonate was being precipitated. These deposits occur as impersistent lenses between lava flows and also as angular blocks in the base of the overlying lavas. This indicates that lithification of the deposit had occurred before the subsequent episode of volcanic activity.

One of the most important questions to attempt to answer in this investigation is the source of the permineralizing carbonate and silica. Leys (1983) describes tuffs from the Saefell tuff ring, Iceland, which contained plant debris and some 'flow aligned fossilized grass stems'. These he describes as having been replaced by gypsum and calcite or are preserved as casts. What is clear at Pettycur is that there has been no replacement or coating of the plant material but an infiltration of carbonate has occurred at the cellular level. Leys (unpub. PhD. thesis, Univ. Leeds, 1982) demonstrates that carbonate minerals are released in some modern and fossil volcanic environment. At Oxroad Bay, East Lothian, permineralized plants are associated with tuff ring volcanism (Scott & Rex, 1986) but here the permineralization is chemically and mineralogically different.

Hay & Iijima (1968) describe palagonite tuffs from Hawaii (palagonite forms from the breakdown of volcanic glass). During the formation of palagonite zeolites, montmorillonite, opal and calcite are liberated. The liberated calcite is abundant forming a coarse-grained cement, filling cavities and forming veins. Analysis of the calcite showed that it was nearly pure with some Mg in a few of the less palagonized tuffs. In modern and ancient tuff ring type volcanoes it appears, therefore, that calcite is readily liberated from the breakdown of ashes. At Pettycur little ash is preserved at the present day and the area is dominated by basaltic lava flows with few interbedded agglomerates and ashes. These lavas are full of secondary carbonate in the form of amygdales, pipes, veins and overprinting the basaltic groundmass. Calcite also occurs as a breakdown product of olivine phenocrysts. Therefore after eruption and consolidation these lavas were permeated by carbonate-rich solutions and to a less extent silica-rich solutions. Whether this carbonate was liberated from the breakdown of the pyroclastics or from the chemical alteration of the lavas, i.e. breakdown of calcic plagioclase, is difficult to assess. It seems clear that carbonate release was closely associated with the volcanic activity and subsequent groundwater activity. These carbonate solutions periodically permeated the growth sites of plants, which had colonized the volcanic surface, and the sites where plant fragments had been deposited, such as small lakes and pools, on the lava surface. The plant-bearing sections at Pettycur are overlain by marine sediments, and no doubt the sea was present at the margins of this area during Dinantian time, but there is no evidence that it provided a source of carbonate.

7. Palaeoecological controls within a basaltic volcanic province

There are several important fundamental controls that have given rise to a fossil plant assemblage. These must be taken into consideration when attempting to understand the original ecology of the plants (Scott & Collinson, 1983*a*,*b*). These include firstly, the original living flora and ecology; secondly, the processes of transport and deposition which moved the plants from their site of growth to their site of fossilization; thirdly, the process of fossilization, whether the plant was permineralized, compressed or fusainized; and finally the possibility of reworking of the plants once they had been fossilized.

During the course of this investigation of the plant-bearing sediments at Pettycur it had been possible by sedimentary and petrological studies to recognize a number of distinct lithologies each with a specific plant assemblage. This has enabled us to propose a hypothesis on the original ecology of the plants living within a basaltic volcanic province during Lower Carboniferous times.

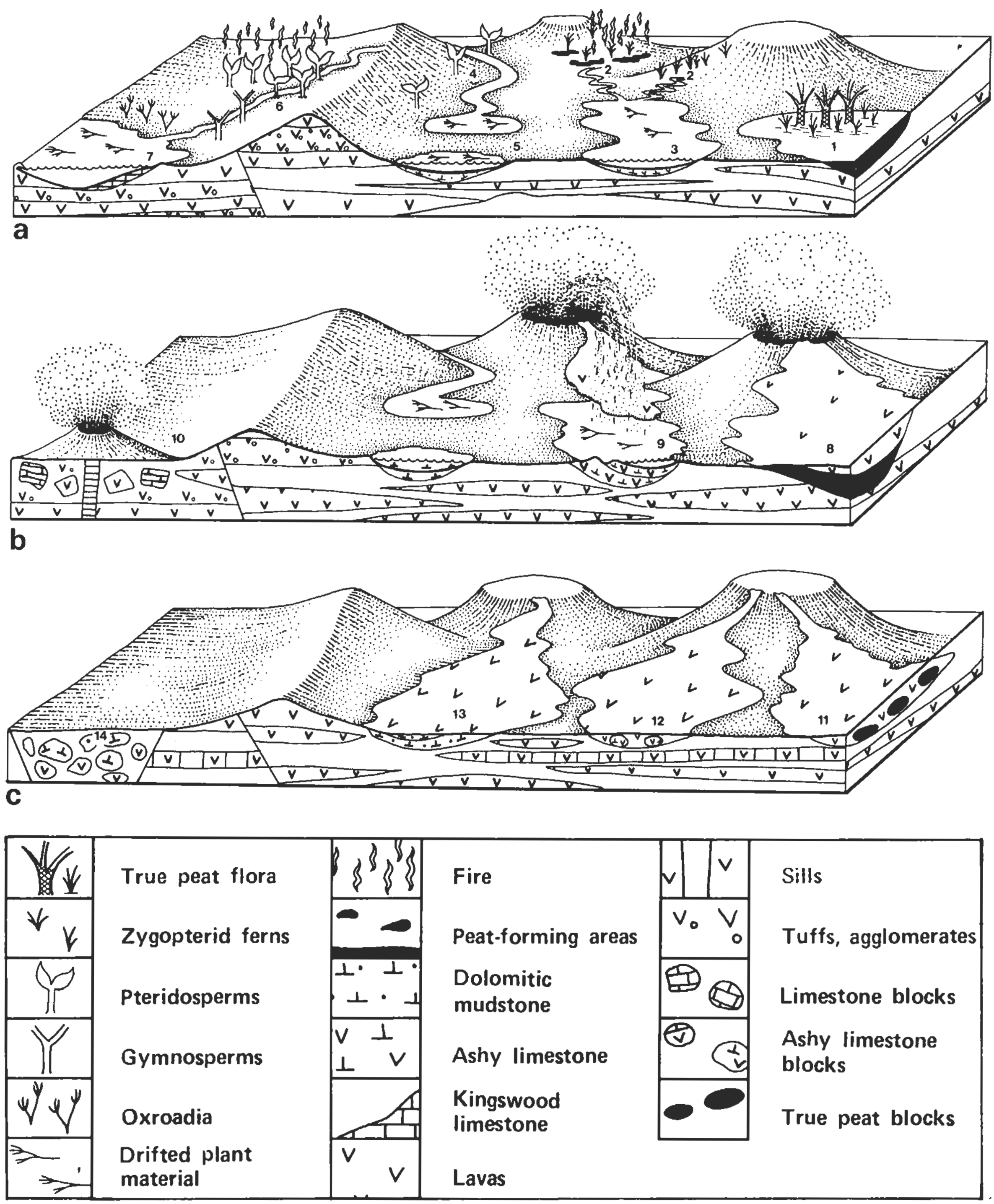
Even though the Pettycur Limestone was never found *in situ* it seems clear that it represents the mineralization of a peat swamp flora established within the province. The peat is dominated by a specific flora of *Paralycopodites–Heterangium–Botryopteris–Stauropteris–Archaeocalamites*. The abundance of stigmarian rootlets indicates that this lithology represents an established peat on which a diverse flora was growing, dominated by lycopods and the pteridosperm, *Heterangium*. The layering of the components of the flora within the peat suggests that certain plants dominated the flora at different times. The evidence from the Pettycur Limestone indicates that this peat swamp was established during a period of quiescence in the volcanic activity. The absence of ash and very rare fusain implies that there was no nearby volcanic centre. Alternatively, the peat may have been forming at a considerable distance from the volcanoes and due to the ability of basalt to flow over large distances was transported into the region.

The second flora recognized at Pettycur occurs within the Zygopterid Limestones. This lithology is dominated by the ferns *Metaclepsydropsis* and *Diplolabis* preserved as permineralizations, fusain or frequently partially fusainized and partially permineralized. The abundance of fusain and clastics within this lithology implies that the zygopterid ferns were growing in a site which was susceptible to wildfire and to ash fall. Within the volcanic setting it seems likely that this was close to eruptive centres. The zygopterid ferns never established a peat-swamp habitat as in the case of the Pettycur Limestone flora. The evidence from the Harbour Peat suggests local, small-scale accumulations of plant material. This peat, though, contains abundant clastics supporting the hypothesis that these plants established themselves near volcanic centres. It may be that the zygopterid ferns represent the pioneer vegetation which, during quiescent periods in the volcanic activity, established small-scale areas of peat which were frequently burnt. The complete absence of the zygopterid ferns from the Pettycur Limestone indicates that these two floras were growing in different ecological sites. Components of these two main Pettycur floras were, from time to time, transported into small lakes on the lava surface within which ashy limestones were forming.

The flora from the Kingswood Limestone represents a very different plant assemblage from that found within the Pettycur Limestone and associated plant-bearing sediments. The plants preserved at Kingswood represent two distinct components. The lycopod (*Oxroadia*) which is preserved in the limestone is very different from any of the lycopods preserved at Pettycur. *Oxroadia* and some of the gymnosperms occur permineralized within the sediment whereas the pteridosperms, forming the bulk of the flora, are almost always fusainized. All the plants are usually fragmented. It is proposed that the lycopod and some of the gymnosperms were living near to, but not on the margins of a lake. In contrast, the pteridosperms were growing in an area that was susceptible to wildfire, were fragmented during transport and deposited into the lake along with the plants being permineralized. One of the great difficulties in interpreting this Kingswood flora is that the flora is completely different from that outcropping at the present day only 0.5 km away at Pettycur. There are several possible explanations for this phenomenon. Firstly, that these two floras were separated by a time interval and were established at different times. The floras occur at the same stratigraphic horizon and it is difficult to assess what this interval may have been. A second possibility is that the original growth sites were separated by a considerable distance and it is the subsequent processes of transport, deposition and further reworking that has brought them into proximity. It is more likely that the Pettycur flora has been transported a greater distance than the Kingswood flora as it occurs in the base of lava flows. The Kingswood flora is preserved in large blocks within an agglomerate sequence and may be reasonably close to the original site of limestone deposition. The third possibility is that here an original ecology is being reflected and the two floras existed in differing habitats which were separated from each other not by time but by some natural barrier.

Some specimens of *Archaeocalamites* from the Kingswood locality show pronounced growth rings (Scott *et al.* 1986, pl. 3). Most palaeogeographic reconstructions for the Lower Carboniferous (Visean)

Figure 18. Hypothetical reconstruction of the original palaeoecology, deposition and fossilization of the plant deposits at Pettycur. (a) Original palaeoecology showing growth and fossilization sites. The Pettycur Limestone flora (1) established a peat-forming area on the volcanic surface during a period of quiescence in the volcanic activity. The zygopterid ferns (2) established small-scale peat areas which were frequently burnt and the plants transported into small lakes (3) where carbonate was being precipitated. Pteridosperms grew in a separate site (4) and were transported as debris into small lakes on the volcanic surface in which dolomitic mudstones were being deposited (5). The Kingswood flora was separated by time or a barrier as shown here from the Pettycur flora. In this area pteridosperms and gymnosperms grew at some distance from the lake, were frequently burnt and transported into the lake as fusain (6). Nearer the lake *Oxroadia* (7) grew and was washed into the lake and permineralized in the limestone that was being deposited. (b) Subsequent period of eruption of nearby volcanic centres. This results in a series of ash falls and lava flows which destroy the peat-forming areas (8) and the zygopterid limestones (9). A nearby eruption destroys the Kingswood Limestone (10) resulting in brecciation and incorporation in a pyroclastic series. (c) Final burial and relative positions of the plant-bearing deposits at the present day. The true peat lithology (11) and the Zygopterid Limestone and ashy limestones (12) are incorporated into the base of basaltic lavas which flowed over the lithified deposits. Plant compression fossils occur within dolomitic mudstones (13) which outcrop between lava flows. The Kingswood Limestone (14) occurs as blocks within an agglomerate sequence which may represent a down-faulted block formed as a result of subsidence in the volcanic terrain.



show Scotland on or just north of the equator, with a wet or humid, seasonless climate (Rowley *et al.* 1985). This analysis is broadly confirmed by the absence of growth rings in fossil wood from northern Britain (Creber & Chaloner, 1984*a*). There are numerous factors which may result in the formation of growth rings apart from climatic seasonality (Creber & Chaloner, 1984*b*). If the plant was living on a thin porous soil then variation in water availability may result in the formation of rings (Creber & Chaloner, 1984*b*). It has also been demonstrated that major volcanic eruptions may influence the local climate which may show up in the tree-ring record (La Marche & Hirschbueck, 1984). Until a wider study of the growth rings of Lower Carboniferous trees from southern Scotland has been undertaken it would perhaps be unwise to place any regional palaeoclimatic interpretations on these growth rings found at Kingswood.

The final assemblage recognized within the region is the compression flora occurring in the calcareous mudstones that outcrop on the tops of the basalt lava flows. This flora is dominated by pteridosperm-like foliage and lycopods. Relating compressed and permineralized pteridosperms is very difficult because of the contrast in the level of information available from the different preservation states (Galtier, 1986). It is possible that it is the same taxa present in both fossilization states at Pettycur but it is impossible to recognize. The problem is even more difficult with ferns as they were small in life (less than 0.5 cm in diameter), bore very fine lamina and are very difficult to recognize in the compression state of preservation and may well be discarded by the collector as worthless scraps of organic matter. The compressed flora at Pettycur seems to have been transported or washed into small pools that developed on the old lava surfaces. They may well have been transported a considerable distance from their growth site which was possibly situated well away from the volcanic area.

We offer here, therefore, a first hypothesis to explain the original ecology of the floras growing in the Pettycur region during Lower Carboniferous times. The tentative model we propose takes into account original sites of growth, transport, deposition and subsequent fossilization and reworking but does not take into account the factors of relative distance, time and possible climatic change. Our hypothetical reconstruction is shown in Figure 18.

8. Summary

The preservation of the plant deposits of Lower Carboniferous (Asbian) age of the Pettycur region, Fife, Scotland has been investigated. A number of distinct plant assemblages have been recognized within the area:

(1) The Pettycur Limestone containing a distinct plant assemblage of *Paralycopodites–Heterangium–Botryopteris–Stauropteris–Archaeocalamites*. The limestone exhibits a characteristic mineralization and represents the fossilization of a peat established within the terrain. The zygopterid ferns are noticeably absent from this lithology.

(2) A Zygopterid Limestone dominated by two ferns *Diplolabis* and *Metaclepsydropsis* which are preserved both as permineralizations and fusain.

(3) A number of ashy limestones dominated by the zygopterid ferns but showing evidence of transport before fossilization.

(4) The Kingswood Limestone composed of pteridosperms preserved as fusain and some gymnosperms and *Oxroadia* as permineralizations. This flora has only one taxon in common with the Pettycur flora even though at the present day the outcrops are only separated by 0.5 km.

(5) A series of dolomitic mudstones containing pteridosperms and lycopods preserved as compressions.

Within each of the permineralized plant-bearing lithologies the mineralization is distinctive. This is related to fossilization either within a growth site or within a site of deposition of plant fragments. The dominant permineralizing mineral is calcite but silica is also present. The minerals were derived probably from the alteration of the lavas and pyroclastics which provided carbonate- and silica-rich solutions which permeated the area. Fossilization by a hot-spring or tufa type of deposition or from a marine source seems unlikely. All the lithified plant deposits were subsequently destroyed by the volcanic activity and transported in the base of lava flows or included in agglomerates. A first hypothesis is offered to explain the original ecology of the plants and their subsequent transport, deposition and fossilization histories.

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References

ALLAN, D. A. 1924. The igneous geology of the Burntisland district. *Transactions of the Royal Society of Edinburgh* **53**, 479–501.

BENSON, M. J. 1914. *Sphaerostoma ovale* (*Conostoma ovale* et *intermedium*, Williamson), a Lower Carboniferous ovule from Pettycur, Fifeshire, Scotland. *Transactions of the Royal Society of Edinburgh* **50**, 1–16.

BRACK-HANES, S. D. & THOMAS, B. A. 1983. A re-examination of *Lepidostrobus* Brongniart. *Botanical Journal of the Linnean Society* **86**, 125–33.

CHALONER, W. C. & COPE, M. J. 1982. Interaction of plant evolution, wildfire, atmospheric composition and climate. *Proceedings of the Third North American Palaeontological Convention* **1**, 83–5.

CLAYTON, G. 1986. Plant miospores and Dinantian intercontinental correlation. *Dixième Congrès International de Stratigraphie et de Géologie du Carbonifère, Madrid*, **4**, 9–23.

COPE, M. J. & CHALONER, W. G. 1980. Fossil charcoal as evidence of past atmospheric composition. Nature **283**, 647–9.

CREBER, G. T. & CHALONER, W. G. 1984*a*. Climatic indications from growth rings in fossil wood. in *Fossils and Climate* (ed. P. Brenchley) pp. 49–73. Chichester: Wiley.

CREBER, G. T. & CHALONER, W. G. 1984*b*. Influence of environmental factors on the wood structure of living and fossil trees. *Botanical Review* **50**, 357–448.

DICKSON, J. A. D. 1965. Carbonate identification and genesis as revealed by staining. *Journal of Sedimentary Petrology* **36**, 491–505.

FRANCIS, E. H. 1960. An excursion guide, Burntisland to Kirkaldy. In *Edinburgh Geology* (eds. G. H. Mitchell, E. K. Walton & D. Grant), pp. 206–13. Edinburgh: Oliver & Boyd.

FRANCIS, E. H. 1978. Igneous activity in a fractured craton, Carboniferous volcanism in Northern Britain, in *Crustal Evolution in Northwest Britain and Adjacent Regions* (ed. D. R. Bowes and B. E. Leake), pp. 279–96. Geological Journal Special Issue, no 10.

FRANCIS, E. H. 1983*a*. Carboniferous. In *Geology of Scotland* (ed. G. Y. Craig), pp. 253–96. Edinburgh: Scottish Academic Press.

FRANCIS, E. H. 1983*b*. Carboniferous-Permian igenous rocks. In *Geology of Scotland* (ed G. Y. Craig), pp. 297–324. Edinburgh: Scottish Academic Press.

FRANCIS, E. H. & HOPGOOD, A. M. 1970. Volcanism and the Adross Fault, Fife, Scotland. *Scottish Journal of Geology* **6**, 162–85.

GALTIER, J. 1986. Comparing compression and permineralized taxa. In *Systematic and Taxonomic Approaches in Palaeobotany* (ed. R. A. Spicer and B. A. Thomas). Systematics Association Series No 31 (in press).

GEORGE, T. N., JOHNSON, G. A. L., MITCHELL, M., PRENTICE, J. E., RAMSBOTTOM, W. H. C., SEVASTOPULO, G. D., & WILSON, R. B. 1976. A correlation of the Dinantian rocks in the British Isles. *Geological Society of London Special Reports* 7, 1–87.

GEIKIE, A. 1900. The geology of Central and Western Fife and Kinross. *Memoirs of the Geological Survey of Scotland.*

GORDON, W. T. 1909. On the nature and occurrence of the plant-bearing rocks at Pettycur, Fife. *Transactions of the Edinburgh Geological Society* **9**, 355–60.

GORDON, W. T. 1910*a*. Note on the prothallus of *Lepidodendron veltheimianum*. *Annals of Botany* **24**, 821–2.

GORDON, W. T. 1910*b*. On a new species of *Phytostoma* from the Lower Carboniferous rocks of Pettycur (Fife). *Proceedings of the Cambridge Philosophical Society* **15**, 395–7.

GORDON, W. T. 1911*a*. On the structure and affinities of *Diplolabis romeri* (Solms). *Transactions of the Royal Society of Edinburgh* **47**, 711–36.

GORDON, W. T. 1911*b*. On the structure and affinities of *Metaclepsydropsis duplex* (Williamson). *Transactions of the Royal Society of Edinburgh* **48**, 163–90.

GORDON, W. T. 1912. On *Rhetinangium arberi*, a new genus of Cycadofilices from the Carboniferous Sandstone Series. *Transactions of the Royal Society of Edinburgh* **48**, 813–25.

GORDON, W. T. 1914. The country between Burntisland and Kirkaldy. *Proceedings of the Geologists' Association* **25**, 34–9.

HAZELDINE, R. S. 1984. Carboniferous North Atlantic palaeogeography: stratigraphic evidence for rifting, not megashear or subduction. *Geological Magazine* **121**, 443–63.

HAY, R. L. & IIJIMA, A. 1968. Nature and origin of palagonite tuffs of the Honolulu Group on Oahu, Hawaii. *Memoirs of the Geological Society of America* **116**, 331–76.

JOY, K. W., WILLIS, A. J. & LACEY, W. S. 1956. A rapid cellulose technique in palaeobotany. *Annals of Botany N.S.* **20**, 635–7.

KIDSTON, R. 1907. Note on a new species of *Lepidodendron* from Pettycur (*Lepidodendron pettycurensis*). *Proceedings of the Royal Society of Edinburgh* **27**, 207–9.

KIDSTON, R. 1908. On a new species of *Dineuron* and of *Botryopteris* from Pettycur, Fife.*Transactions of the Royal Society of Edinburgh* **46**, 361–4.

LA MARCHE JR, V. C. & HIRSCHBUECK, K. K. 1984. Frost rings in trees as records of major volcanic eruptions. *Nature* **307**, 121–6.

LEEDER, M. R. 1976. Sedimentary facies and the origins of basin subsidence along the northern margin of the supposed Hercynian ocean. *Tectonophysics* **36**, 167–79.

LEEDER, M. R. 1986. Plate tectonics, palaeogeography and sedimentation in Lower Carboniferous Europe. In *European Dinantian Environments* (eds. J. Miller, A. E. Adams and V. P. Wright), pp. 1–20. Geological Journal Special Issue no. 12.

LEYS, C. A. 1983. Volcanic and sedimentary processes during the formation of the Saefell tuff-ring, Iceland. *Transactions of the Royal Society of Edinburgh; Earth Sciences* **74**, 15–22.

MEYER-BERTHAUD, B. 1986. *Melissotheca* gen.nov. a pollen organ from the Upper Visean of Scotland. *Botanical Journal of the Linnean Society* **93**.

MEYER-BERTHAUD, B. & GALTIER, J. 1986. Studies on a Lower Carboniferous flora from Kingswood near Pettycur, Scotland. II. *Phacelotheca*- a new synangiate fructification of pteridospermous affinities. *Review of Palaeobotany and Palynology* **48**, 181–98.

PETTIJOHN, F. J. 1957. *Sedimentary Rocks* New York: Harper & Row.

REX, G. M. & CHALONER, W. G. 1983. The experimental formation of plant compression fossils. *Palaeontology* **26**, 231–52.

ROWLEY, D. B., RAYMOND, A., PARRISH, J. T., LOTTES, A. L., SCOTESE, C. R. & ZEIGLER, A. M. 1985. Carboniferous palaeogeographic, photogeographic and palaeoclimatic reconstructions. *International Journal of Coal Geology* **5**, 7–42.

SCHOPF, J. M. 1975. Modes of fossil plant preservation. *Review of Palaeobotany and Palynology* **20**, 27–53.

SCOTT, A. C. & COLLINSON, M. E. 1978. Organic sedimentary particles: results from the SEM of sedimentary particles. In *SEM and the Study of Sediments* (ed. W. B. Whalley). pp. 137–67. Geoabstracts.

SCOTT, A. C. & COLLINSON, M. E. 1983*a*. Investigating fossil plant beds. Part 1. The origin of fossil plants and their sediments. *Geology Teaching* **7**, 114–22.

SCOTT, A. C. & COLLINSON, M. C. 1983*b*. Investigating fossil plant beds. Part 2. Methods of palaeoenvironmental analysis and modelling and suggestions for experimental work. *Geology Teaching* **8**, 12–26.

SCOTT, A. C., GALTIER, J. & CLAYTON, G. 1984. The distribution of Lower Carboniferous anatomically preserved floras in Western Europe. *Transactions of the Royal Society of Edinburgh; Earth Sciences* **75**, 311–40.

SCOTT, A. C., MEYER-BERTHAUD, B., GALTIER, J., REX, G. M., BRINDLEY, S. A. & CLAYTON, G. 1986. Studies on a Lower Carboniferous flora from Kingswood near Pettycur, Scotland. I. Preliminary Report. *Review of Palaeobotany and Palynology* **48**, 161–80.

SCOTT, A. C. & REX, G. M. 1985. The formation and significance of Carboniferous coal balls. In *Extraordinary Fossil Biotas: Their Ecological and Evolutionary Significance* (ed. H. B. Whittington and S. Conway Morris), pp. 123–39. *Philosophical Transactions of the Royal Society B* **311**.

SCOTT, A. C. & REX, G. M. 1986. The accumulation and preservation of Dinantian plants from Scotland and its Borders. In *European Dinantian Environments* (eds. J. Miller, A. E. Adams and V. P. Wright), pp. 329–44. Geological Journal Special Issue no. 12.

SCOTT, D. H. 1898. On the structure and affinities of fossil plants from the Palaeozoic rocks. Pt. 1. On *Cheirostrobus. Philosophical Transactions of the Royal Society of London* B **189**, 1–34.

SCOTT, D. H. 1900. *Studies in Fossil Botany*. London: A. & C. Black.

SCOTT, D. H. 1901. On the seed-like fructification of *Lepidocarpon. Philosophical Transactions of the Royal Society of London* B **194**, 291–333.

SCOTT, D. H. 1920. *Studies in Fossil Botany*. 3rd ed. Part I. London.

SCURFIELD, G., SEQUIT, E. R. & ANDERSON, C. A. 1974. Silicification of wood. *Proceedings of the Workshop on Scanning Electron Microscopes and the Plant Sciences*. IIT Research Institute, Chicago, 389–96.

STEWART, W. N. & TAYLOR, T. N. 1965. The peel technique. In *Handbook of Palaeontological Techniques* (ed. B. Kummel and D. Raup), pp. 224–32. San Francisco: W. H. Freeman.

STOPES, M. C. & WATSON, D. M. S. 1908. On the present distribution and origin of the calcareous concretions in coal seams known as coal balls. *Philosophical Transactions of the Royal Society of London* B **200**, 167–218.

WILLIAMSON, W. C. 1871–95. On the organisation of the fossil plants of the Coal Measures. Parts 1–19. *Philosophical Transactions of the Royal Society of London* **161–184.**

WILLIAMSON, W. C. & SCOTT, D. H. 1895. Further observations on the organisation of the Fossil Plants of the Coal Measures. 1. *Philosophical Transactions of the Royal Society of London* **185**, 863–99.